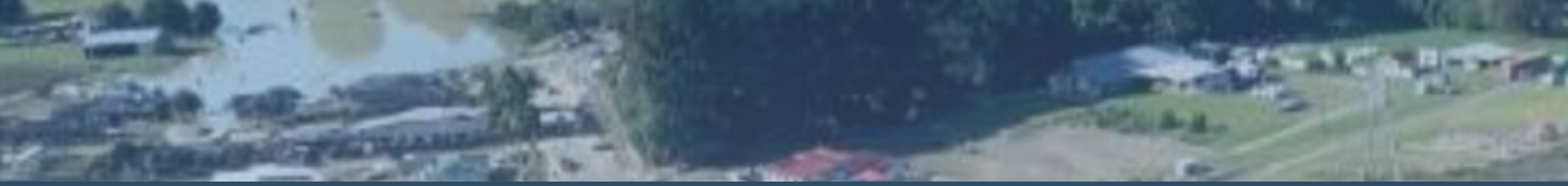

MBIE Extreme Weather Science Response Funding

Supporting Critical Infrastructure Recovery

# Building resilience through recovery: investment decision-making

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RESILIENCE TO NATURE'S CHALLENGES
Kia manawaroa – Ngā Ākina o Te Ao Tūroa
National SCIENCE Challenges

With funding from

MINISTRY OF BUSINESS, INNOVATION & EMPLOYMENT
HĪKINA WHAKATUTUKI

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## Supplementary document

A policy brief summarising the contents of this report is available at resorgs.org.nz/wp-content/uploads/2023/07/NIEWE_critical_Infrastructure_resilience.pdf.

# Contents

# Introduction

The 2023 North Island Extreme Weather Events – including the January floods in Auckland and Cyclone Gabrielle in February – have highlighted the vulnerability of critical infrastructure systems to disruptive events. These catastrophic occurrences caused significant damage to infrastructure systems, leaving some communities without essential services for weeks.

The systems necessary for sustaining human life and societal functions are deemed critical infrastructure and play a crucial role in ensuring the well-being of communities (CIRCA, 2021; Hay et al., 2019). The concept of critical infrastructure goes beyond individual assets to how the individual components fit together in a system to support communities (Hay et al., 2019). It is paramount to build resilience into critical infrastructure to ensure the long-term sustainability and functionality of essential services, particularly in the face of increasingly frequent and severe disruptive events.

To address the challenges posed by climate change and other hazards, it is essential to incorporate resilience considerations in the early stages of project development (ADB, 2021). Mainstreaming resilience into the initial design and construction processes of critical infrastructure is vital to the continuity of services during disruptive events. Proactively integrating resilience measures can lead to substantial cost savings in the aftermath of disruptive events (Hughes & Healy, 2014). Research from the United States has estimated that investing $1 in resilience can save between $4 and $11 in potential recovery costs, making resilience a prudent and cost-efficient strategy (EPA, 2020).

Recovery following disruptive events provides an opportunity to improve critical infrastructure systems' resilience. Strategic investment in repair and reinstatement works can reduce infrastructure system vulnerabilities and increase the future capacity of systems to respond and recover from disruptive events and to adapt to long-term stressors and change (OECD, 2021).

To support the integration of resilience into critical infrastructure planning, we have reviewed critical infrastructure resilience frameworks from around the world. The research was commissioned to support recovery efforts following the 2023 North Island Extreme Weather Events, with funding from the MBIE Extreme Weather Science Response initiative (MBIE, 2023). The analysis aims to identify innovative approaches and best practices to effectively integrate resilience considerations into infrastructure repair and rebuild investment decision-making.

The structure of this report broadly follows the decision-making processes found in many of the resilience frameworks investigated (for example, CISA, 2022; Japan Government, 2018; Leiter et al., 2021; Stout et al., 2019). There are generally six stages of analysis and decision-making:

Stage 1. Problem Definition
Stage 2. Hazard and Damage Assessment
Stage 3. Criticality Assessment
Stage 4. Plan or Option Development
Stage 5. Plan or Option Selection
Stage 6. Implementation

Each section in this report outlines the key considerations and points of interest for each stage. While this report is presented as an end-to-end decision-making framework, elements from this document could be merged into current decision-making processes. This integration can bolster existing planning methods, ensuring a more effective evaluation of resilience considerations.

# Stage 1: Problem definition

The problem-framing stage is the crucial first step in resilience planning (Stout et al., 2019). It involves identifying objectives and clearly defining the challenges that need to be addressed to enhance the resilience of critical infrastructure systems to future hazard events, stressors, and change (EPA, 2020). By accurately defining the problem, decision-makers can lay the foundation for developing effective strategies and actions to mitigate risks, enhance preparedness, and build resilience in alignment with the wider community and national objectives (Gencer, 2017). Considerations as part of the problem-framing stage include:

## Key community needs

When creating a resilient infrastructure plan for a community, it is important to identify the essential functions that are crucial for the well-being and survival of the community (NIST, 2020; Stout et al., 2019). Examples of these functions include warmth, energy, emergency services, communications, economic activity, government services, religious & cultural practices, health services, media, fast-moving consumer goods (FMCG), corrections facilities, potable water, wastewater, and waste management (CISA, 2022; Gallego-Lopez & Essex, 2016; NIST, 2020; Roberts et al., 2020; UNDRR, 2022). Understanding the functions required by society and then determining the infrastructure necessary to support these functions becomes the foundation for building a resilient system. Decision-making should prioritise maintaining these functions, rather than simply providing infrastructure services. This encourages thinking about alternative approaches to service delivery to maintain these essential functions. For example, potable water in urban areas is often provided through a centralised pipe system. While strengthening pipes is an option to build resilience, so is an alternative means of delivering the function such as onsite water storage or water trucks.

The goal is to develop a system that, following disruption, can be restored in a way that ensures essential functions are efficiently and effectively supported to maintain community well-being. This is based on levels of function defined by stakeholders (Culler et al., 2021; Hay et al., 2019). Community needs may vary among different sectors and areas and may change throughout the recovery process (Hughes & Healy, 2014). Understanding the minimum level of service required to meet these functions, and exploring alternative ways to meet functional requirements, becomes crucial. Recovery time performance goals are a good way to articulate expected service over time – both to aid with infrastructure planning and to set clear service expectations for the community. Goals should be created alongside communities based on the community's social functions and infrastructure interdependencies (NIST, 2020).

## Inclusivity

It is important that resilience planning takes into account the needs of the whole community, including those of vulnerable populations (CIRCA, 2021). Vulnerable populations are often worse off during disruptive events (ADPC, 2015; EPA, 2020). Infrastructure decision-makers must understand and identify the unique requirements of different groups to ensure that infrastructure systems are designed and managed in a way that accommodates everyone (Japan Government, 2018).

To achieve this, decision-makers should actively seek input and consultation from the public, considering a wide range of perspectives and requirements across gender, age, ability, and ethnicity including both permanent and temporary residents (such as tourists) (Gencer, 2017; Japan Government, 2018).

By incorporating these diverse views and needs into planning, infrastructure decision-makers can create more inclusive and equitable solutions that address the unique challenges faced by different segments of the population, promoting community-wide resilience. Specific needs should be identified in consultation with the public and in partnership with Iwi and key community stakeholders to provide guidance for, and based on, each specific community (Hay et al., 2019; Infrastructure Australia, 2022; NIST, 2020).

# Interdependencies

Interdependencies between critical infrastructure networks and services are a crucial consideration in resilience planning, as no infrastructure asset operates in isolation (Infrastructure Australia, 2022). The failure of a single asset can have far-reaching consequences if interdependencies allow impacts to cascade into other infrastructure, social, environmental, and economic systems (Infrastructure Australia, 2022; NIST, 2020). To ensure interdependencies are adequately planned for, it is essential to understand the dependencies within and between critical infrastructure systems, looking at those that depend on you and those you depend on (CISA, 2022).

Understanding complex interdependencies and vulnerabilities across infrastructure systems involves identifying the connections and reliance between different assets (Figure 1) (UNDRR, 2022). This can be achieved through workshops or modelling exercises that examine physical, informational, geographic, and logical connections (Rinaldi et al., 2001). Physical connections involve direct dependencies between assets, where one relies on another to function. Informational dependencies require data exchange for optimal operation, while geographic connections involve co-located assets that could impact each other's functionality. Logical connections encompass human factors such as legislation, financial markets, supply chains, etc. Existing networks like regional civil defence lifeline groups can serve as an important vehicle for exploring and analysing these interdependencies.

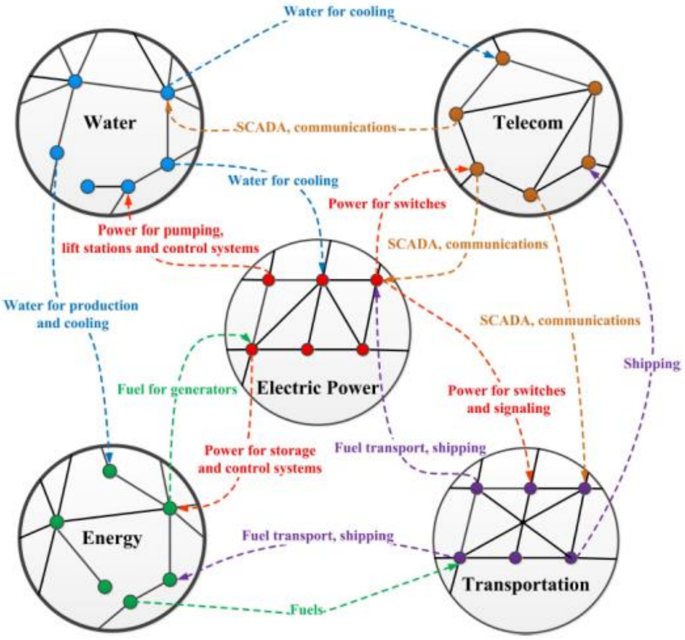

*Figure 1 - Critical infrastructure as a network of networks with no assets existing in isolation (Jianxi et al., 2014).*

Some critical infrastructure assets may not provide direct services to the community they are located within, but are crucial to other communities, the region, or the nation's overall functioning (CISA, 2022).

For example, Manapouri Power Station near Te Anau is a critical piece of infrastructure for Invercargill, 130 km away, with much of the local economy tied to the industry serviced by the dam. Understanding and accounting for these interdependencies in infrastructure plans is vital for continuing business operations in non-affected areas during disasters and preventing economic stagnation at a national level (Japan Government, 2018).

## Stakeholder engagement

Stakeholder engagement is fundamental throughout the planning and implementation stages of critical infrastructure development (ADPC, 2015) (Gencer, 2017). Identifying and involving all relevant stakeholders, including first responders, infrastructure owner-operators, and regional and national disaster management organisations, is essential for coordinated planning (Infrastructure Australia, 2022). Engaging in discussions with these stakeholders helps estimate the duration of disruptions, prioritise reinstatement based on dependencies, and identify available resources and support during response and recovery efforts (Hughes & Healy, 2014). This in turn helps identify priorities for pre-event investment in infrastructure. Quality engagement also helps to build trust between government and infrastructure operators, fostering effective collaboration and partnership-building (UNDRR, 2022).

Building the resilience of critical infrastructure is a joint effort between all stakeholders. Collaboration should extend to include community members, iwi, and local and national government agencies, ensuring integration and alignment with their needs and expectations (Victoria State Government, 2015). Giving consideration to changing community expectations and social connectivity is also essential to create resilient infrastructure that meets the evolving needs of society (OECD, 2021). The inclusion of community in the design and planning phases of infrastructure projects, through participatory mechanisms such as consultations or deliberative processes, strengthens public support and provides legitimacy to public spending (Gallego-Lopez & Essex, 2016; OECD, 2021).

# Stage 2: Hazard and damage assessment

Understanding the type and extent of hazards that systems are exposed to can aid in estimating the expected damage to assets for a given event. These direct damage predictions can then be leveraged to identify likely disruption to communities through loss of infrastructure services. This analysis can aid in the prioritisation and design of infrastructure plans.

When the hazards are well understood and there are predictions or statistical representations of what could happen, we suggest taking a hazard-based approach where actions are designed for an expected disruption. Incorporating risk assessments into the planning process lets decision-makers prioritise, plans, select effective options, and ensure the development of infrastructure systems that can withstand and recover from disruptive events with greater resilience. When there is substantial uncertainty around what could happen, an intervention-based approach could be used. In an intervention-based approach, plans are designed to be resilient across a range of possible impacts. While this approach may contribute to greater robustness across disruption types, because of the uncertainty in the analysis solutions may be less efficient than those arising from a hazard-based approach. Each approach is explained in more detail below.

# Hazard-based approach

A hazard-based approach is built on the combination of hazard information, asset exposure and asset vulnerability data (Figure 2). It uses probabilities or scenarios to estimate damages to infrastructure following a disruptive event  (Hughes & Healy, 2014, APA, 2014).

This information can then be used in combination with a criticality assessment (see Stage 3 below) to prioritise plans, and again in the option selection stage (see Stage 5 below), to provide quantitative measures of resilience. Because of the reliance on data to predict hazards and impacts, hazard-based approaches are effective in situations where there is an understanding of what could happen. Plans are then designed to work under these predicted outcomes in a process called agree-on-assumptions.

*Figure 2 - Risk is the combination of hazard, exposure, and vulnerability (United Nations n.d.)*

To comprehensively assess and understand the risks posed by natural hazards, a risk assessment needs to consider a wide range of hazards and their potential severity (now and in the future) while also considering all key infrastructure systems (APA, 2014) (Victoria State Government, 2017).

Risk assessments should encompass all hazards that could affect the relevant assets. This data can be obtained from a wide range of sources, including trends, expert insights, modelled hazard projections, and historical data. While historical data can provide insights into hazards and consequences, care must be taken as plans need to be forward-looking, showing how hazards might occur in the future (Gallego-Lopez & Essex, 2016; NIST, 2020). Because hazards can occur concurrently, multi-hazard risk analytics are essential for robust planning and assessment of emergency risks (Rashmi et al., 2023). A probabilistic understanding of the combinations of changing hazards is required to integrate potential changes into infrastructure planning and management (ADB, 2021; EPA, 2020; Gallego-Lopez & Essex, 2016; Guenther & Balbus, 2014).

It is also essential to develop a comprehensive map of all critical infrastructure system components to understand how these current and projected threats could impact infrastructure systems (APA, 2014; CISA, 2022; Gencer, 2017; Hay et al., 2019; Stout et al., 2019; Waka Kotahi, n.d.). Overlaying hazard extents like earthquakes, floods, or tsunamis onto assets, identifies the exposure of communities to hazards. Where possible, hazard data should also include intensity (flood depth, windspeed, ground acceleration, etc.). The inclusion of hazard intensity allows for investigation into expected asset damage. Asset damage can be calculated using fragility functions which relate asset type and condition and hazard intensity to expected damage. Fragility functions can be binary, showing the level of hazard above which an asset can no longer function, or continuous, modelling the relationship between hazard severity (e.g., flood height) and degree of asset damage.

Scenario planning could be used in combination with risk modelling as it may not be feasible to test and model all possible scenarios (Culler et al., 2021; Gallego-Lopez & Essex, 2016). Scenarios allow planners to explore various network effects, investigating how failures can cascade through and between infrastructure networks. These scenarios should be plausible representations of the future and include relevant information, such as flood inundation levels or wind speeds that cause damage, to aid decision-makers in comparing options (Stout et al., 2019). Scenarios are developed by asking "what if" questions to stakeholders, considering various hazard combinations and chains of events (Culler et al., 2021).

Ultimately, the risk assessment should identify the specific hazards to which infrastructure is vulnerable and establish a comprehensive understanding of what disruptions communities may experience during a disruptive event. This will inform resilient infrastructure planning and decision-making (Gencer, 2017; NIST, 2020). By predicting the disruptions of an event, decision-makers can understand the loss of function a community may experience, prioritise plans, select effective options, and ensure the development of infrastructure systems that can withstand and recover from disruptive events.

Hazard-based approaches are data-intensive, requiring hazard maps showing the spatial extent of specific hazards and how they may change in the future as well as detailed infrastructure asset data. The quality of a hazard-based approach is often heavily dependent on the amount and quality of both asset and hazard data available, as well as the degree of uncertainty (Infrastructure Australia, 2022; Rashmi et al., 2023; Roberts et al., 2020; UNDRR, 2022). In cases where data is not present, or there is substantial uncertainty in the hazards, an intervention-based approach could be used instead (Hughes & Healy, 2014; OECD, 2021).

## Intervention-based approach

An intervention-based approach flips the hazard-based approach on its head using an agree-on-decisions methodology (Victoria State Government, 2015). Agree-on-decision approaches involve creating plans that work well across a range of future possibilities. This is done by designing plans and then evaluating the potential disruption across a range of possible hazard impacts. This method will create plans that are more robust to uncertainty but may lack the efficiency of hazard-based plans.

Intervention-based approaches apply general robustness concepts to decision-making, circumventing the need for precise data on hazard extents and frequencies. They aim to be resilient to a wide range of events rather than optimised for well-described events. This is done by applying concepts like redundancy and resistance during the plan/option development stage (see Stage 4 below) and then testing plans across hazard scenarios to ensure that plans do measurably improve resilience (see Stage 5 below).

Using an Intervention-based approach does not rely heavily on a risk assessment. During the option selection stage (see Stage 5 below), a range of possible hazard scenarios are required to evaluate the effectiveness of proposed options. The lack of damage data also means that the prioritisation stage (see Stage 3 below) is largely driven by asset or network component criticality (Hughes & Healy, 2014). Even when using intervention-based approaches, an understanding of the range of possible hazards should be sought out (Hay et al., 2019). Regardless of the approach that is taken there will always be some degree of uncertainty, and no infrastructure asset or system can be designed to cope with all possible hazards (UNDRR, 2022).

# Stage 3: Criticality assessment

The criticality assessment stage plays a vital role in resilience planning by identifying and prioritising the impact of the loss of service of a critical infrastructure system on the community/users and key community functions (CISA, 2022; Stout et al., 2019; Victoria State Government, 2015). This moves beyond simply physical disruption and to the likely socio-economic impacts on the community (Culler et al., 2021). By assessing the criticality of each aspect of an infrastructure network/system, decision-makers can allocate resources effectively and prioritise investments in the components of the network that provide the greatest resilience benefits.

The combination of hazards, damage, and criticality is the basis of the hazard-based approach. This information can be used to prioritise planning based on where and what the highest risks are (CISA, 2022). For an intervention-based approach, criticality measures alone can be used to prioritise investment. Many measurements of criticality could be considered individually or in combination. These are discussed below.

## Business as usual (BAU)

One way to measure criticality is by assessing how important an asset/infrastructure system is to business-as-usual operations. This could include the number of people serviced or the importance of a link to supporting other services (otherwise known as interdependencies) (Hughes & Healy, 2014). The service investigated should support key community functions identified in Stage 1. For example, Waka Kotahi uses the One Network Road Classification framework to provide a hierarchy of road importance (Hughes & Healy, 2014). While this classification is a good starting point, some roads may be more critical than represented in this framework. For instance, some lifelines groups classify some roads as nationally or regionally significant, in opposition to the One Network framework (Roberts et al., 2020).

## Recovery

Another way to evaluate criticality is to consider how important assets/infrastructure systems are directly after an event and during the recovery (Roberts et al., 2020). For example, access to a sports field may not be a high priority under BAU classifications but could provide access to helicopter resupplies after a disruption. In Japan, there is a classification of “important logistics roads”. These are not necessarily the highest BAU occupancy roads but are prioritised for protection (pre-event) and recovery (post-event) to ensure resources can still be distributed after a disruptive event (Japan Government, 2018).

## Community and customers disrupted

The number of people and activities serviced by an asset/infrastructure system provides another measure of criticality (APA, 2014). In its simplest form, this includes the number or percentage of customers impacted if an asset/system fails (Stout et al., 2019). Critical customers (e.g., hospitals and civil defence centres) should also be considered as they have a higher consequence of failure (Roberts et al., 2020).

## Interdependencies

The number of critical infrastructure interdependencies also provides a measure of criticality. An asset/infrastructure system becomes more critical as more critical infrastructure assets depend on it (Roberts et al., 2020). To understand this a systems approach is required that identifies interdependencies, supply chains and weakest link vulnerabilities (Hughes & Healy, 2014). Understanding interdependencies allows for cross-sectorial solutions as resilience benefits flow through the networks (ADB, 2021).

Co-location of critical infrastructure assets is a common concern in New Zealand, that is, where infrastructure converges in "pinch points". For example, the co-location of assets on bridges, or narrow transport corridors (Roberts et al., 2020). Disruptions in these sites can impact multiple critical assets simultaneously and failure can have severe impacts, leading to widespread loss of service and amplifying the overall risk and consequence of a potential failure (Roberts et al., 2020).

## Community vulnerability

Some communities are more vulnerable than others, exacerbating the impacts (and therefore risk) to people of disruptive events. For example, communities located in isolated areas are vulnerable to loss of access, which could impact access to food supplies and medical care. Understanding communities vulnerabilities informs the prioritisation and nature of infrastructure investment (APA, 2014). The social deprivation index provides one possible, generalised, proxy for vulnerability.

# Stage 4: Plan or option development

The plan or option development stage involves the formulation and design of robust and coordinated resilience plans or options based on the findings from the desired performance outcomes, hazard assessment, and criticality assessment. Approaches to enhance resilience range from emergency preparedness measures to infrastructure reinforcement and network redesign. A mix of solutions should be considered (Stout et al., 2019).

## Emergency preparedness measures

### Stockpiles and backups

Resource stockpiles, equipment, and backup components enable prompt response and recovery operations during/after disruptive events (Infrastructure Australia, 2022; Japan Government, 2018; Waka Kotahi, n.d.). Ideally, there should be enough resources ready to be able to respond without external support (Japan Government, 2018).

### Recovery support

In addition to having physical resources, communities should have the necessary expertise to implement the backups and support their recovery. This could be achieved or supported through mutual aid agreements (NIST, 2020).

### Alternative service delivery mechanisms

Alternative service delivery mechanisms and strategies should be explored to ensure critical community functions remain operational while business as usual infrastructure system assets and services are compromised or unavailable (Hay et al., 2019). For instance, temporary back-up (water, electricity, communication) systems could be provided until the original supporting infrastructure has been reestablished (NIST, 2020). This is particularly important for services that are required in the response (e.g., hospitals) to ensure the continuity of essential functions during infrastructure outages (Japan Government, 2018).

### Demand management

Measures can be implemented to reduce demand on infrastructure systems. Reducing demand on infrastructure systems makes the system (and users) less susceptible to periods where capacity is reduced by disruption (OECD, 2021). This can be as simple as using LED bulbs to reduce the use of fuel in generators (Guenther & Balbus, 2014). Demand management could be implemented through time-based user charges, technology, or self-regulation by educating users (OECD, 2021).

### Removal of potential hazards

Potential hazards can be removed to decrease the possibility/severity of damage. For example, improvements can be made to slope stability, or trees near powerlines can be pruned (Waka Kotahi, n.d.).

## Network design

### Asset location/exposure

Increasing the resilience of the network may require moving an asset away from hazards to prevent damage and disruption (ADB, 2021; Infrastructure Australia, 2022; Waka Kotahi, n.d.). Decentralisation could serve as a means of minimising the presence of assets in high-risk areas and can minimise the spatial scale of disruption following an event (Japan Government, 2018).

### Hazard diversity

Relocating assets to areas where there are no hazards is often not feasible. Where possible there should be diversification of hazards the network is exposed to. This reduces the chance that all assets would be affected by the same event resulting in a complete loss of service. This concept can be considered at a network or system level, especially when multiple services provide a similar function. For example, many roads and rail lines follow the same route and thus are susceptible to the same hazards and concurrent failure (Roberts et al., 2020).

### Redundancy

Redundancy is created through the inclusion of resources or alternative paths through the system above what is required for business-as-usual conditions (Stout et al., 2019). This could be done through N+1 configuration, Ladder networks, sacrificial components, duplication etc. (Gallego-Lopez & Essex, 2016; Guenther & Balbus, 2014; Hay et al., 2019; Roberts et al., 2020). Redundancy in network design can be difficult in New Zealand due to its geographical nature and low population density (Roberts et al., 2020).

### Robustness

Assets can be strengthened to withstand larger events without loss of service (Gallego-Lopez & Essex, 2016; Hughes & Healy, 2014; Infrastructure Australia, 2022; Japan Government, 2018). This is a common strategy for infrastructure required to support the response and recovery of disruptive events (NIST, 2020).

### Safe-to-fail

Safe-to-fail design allows for controlled failure of an asset on the assumption that the possibility of failure can never fully be eliminated (Gallego-Lopez & Essex, 2016; Hughes & Healy, 2014; Infrastructure Australia, 2022; Waka Kotahi, n.d.). Safe-to-fail considerations includes not just how the asset will fail but how its failure may affect the system/service delivery. This includes how the failure will be mitigated by the presence of emergency response measures, system redundancy and network exposure.

### Adaptative planning

Adaptive planning principles should be applied to infrastructure planning when hazards are changing with time (Infrastructure Australia, 2022; Rashmi et al., 2023). For example, over-engineering foundations allow for future modifications to the structure without the need to redesign/replace previous foundations. This involves monitoring conditions to ensure that assets can resist changing hazards and designing assets to allow for future modification should conditions change (Culler et al., 2021; Waka Kotahi, n.d.). Often this will involve more upfront costs. However, these costs are a hedge against uncertainty. The upfront costs will either offset future costs, where future modifications are required, or they mitigate the potential for over-investment where expected impacts do not eventuate.

Decisions should be made considering the possibility of future managed retreat (EPA, 2020). This includes the future need to retreat assets from areas directly affected by coastal erosion and sea level rise, or the potential future change in demand resulting from communities retreating from certain areas.

## Stage 5: Plan or option selection

The plan or option selection stage focuses on evaluating and selecting the most appropriate resilience plans from the options developed during the plan or option development stage. It involves a careful analysis of the feasibility, effectiveness, and cost-benefit of each plan (APA, 2014; CISA, 2022). Decision-makers need to assess the alignment of the plans with the identified needs, objectives, and priorities set by the community in Stage 1 (CISA, 2022; NIST, 2020).

Any adopted plan or option should have a measurable increase in resilience/performance when comparing plans and options to a “do nothing” baseline scenario (Culler et al., 2021; Gallego-Lopez & Essex, 2016; NIST, 2020). This baseline helps identify the resilience improvements (benefits) that can then be used as part of a CBA and/or in combination with their impact on other community goals and values. **For an intervention-based approach, it is essential to test options across a range of scenarios to explore how the system may react to uncertain conditions. This rebases the intervention-based approach back into risk science**. Possible resilience measurements include:

### Time to recover to pre-event levels

This is simply a measure of how much time it takes to restore as service to normal levels. Time to recover should be estimated alongside other critical infrastructure providers, accounting for interdependencies that could affect the duration of recovery efforts. For example, the time to restore an electricity service may depend on how long it takes to restore road access to the assets that need repair (NIST, 2020).

### Time to recover basic community needs

Related to the above, a measure could be made of the time it takes to restore infrastructure service to an agreed or satisfactory basic level of service (below pre-event levels). As above, this should consider other critical infrastructure providers to account for interdependencies (Culler et al., 2021; Roberts et al., 2020).

### Damages avoided

Damages avoided can be a measure of resilience. This is the value of repair and replacement costs not incurred due to the implementation of the intervention or plan. It is commonly expressed in dollars (APA, 2014).

### Casualties avoided

One possible measure of resilience enhancement is an estimate of how many fewer people would be killed or injured if the plan or option is implemented. This could be a direct result of an event or as part of the recovery if key community functions are not reinstated quickly enough.

### Socio-economic benefits (avoided losses)

Avoided losses is a measure of the indirect socio-economic benefits of an intervention. This can be challenging to estimate but can include business disruption, workforce displacement, interruption to education, health impacts, etc., (APA, 2014; Culler et al., 2021; Gencer, 2017).

### Number of failure mechanisms

Another resilience measure is a count of the failure mechanisms. This is useful for intervention-based approaches where there is uncertainty in the hazards so a reduction in failure mechanisms is directly related to an increase in resilience.

### Number of dependencies within networks

Related to the above, a count of the number of infrastructure systems that rely on each asset or the asset relies on to provide function can be a measure of resilience (NIST, 2020). A reduction in dependencies can stop failures cascading through systems.

### Magnitude of disruptive events able to be withstood

Quantifying the magnitude of disruptive events that an asset or system can withstand is a direct measurement of robustness. This could include the flood height or peak ground acceleration that an asset could resist, or it could be an Annual Exceedance Probability (AEP) that the asset is designed for. Climate change will affect the frequency and severity of climate-related events. This means that system robustness will likely change over time and will need to be monitored.

### Number of systems that have backups and duplicates

Identifying systems with backups and/or duplicates is a direct measurement of redundancy. This could be measured as a percentage of assets that could be replaced.

## Collaboration and consensus

An effective option selection process involves collaboration across, and seeks consensus among various stakeholders to ensure a comprehensive and inclusive resilience planning process, including government entities, industry representatives, Iwi, and community members (CISA, 2022; Japan Government, 2018; Leiter et al., 2021; Stout et al., 2019; UNDRR, 2022). This increases buy-in and ensures plans are stress-tested from multiple perspectives. This could be done via workshops, briefings, collaborative online dialogues and tools, focus groups, etc., (NIST, 2020).

There also needs to be collaboration between infrastructure managers and operators. This will help to align plans across different infrastructure entities leveraging synergies and avoiding trade-offs where possible.

## Synergies and trade-offs with BAU

Synergies with business-as-usual operations should be identified and maximised and trade-offs avoided, where possible. There may be tension between resilience plans and business strategies like just-in-time delivery (Roberts et al., 2020; UNDRR, 2022). For example, building redundancy into the transport network synergises with the goals of connecting communities and provides economic growth.

# Stage 6: Plan or option implementation

The plan implementation stage involves translating the developed plans into actionable initiatives, allocating resources, and coordinating the implementation. This process may adopt a phased approach, prioritising essential community requirements and areas where there is greater vulnerability. In addition to the technical execution of plans, several critical activities underpin effective implementation and ongoing emergency preparedness.

## Stakeholder engagement

Stakeholders and the public should be engaged to ensure they are informed about the recovery process, their roles, the risks they bear, and how they can contribute to infrastructure management after the event (ADPC, 2015; CISA, 2022; EPA, 2020). Regular meetings are helpful to keep communities up to date on progress and for overcoming potential barriers (Gencer, 2017).

## Communication structure

Clear communication and command structures are needed to facilitate effective coordination and decision-making during response and recovery efforts across sectors (Gencer, 2017; Hughes & Healy, 2014; UNDRR, 2022). Multiple communication channels are often necessary to reach everyone, particularly if there are power or communication failures (Japan Government, 2018; Waka Kotahi, n.d.).

## Information sharing

Information systems or standardise data sets are useful to facilitate information sharing and coordination among infrastructure operators and stakeholders during recovery operations (CISA, 2022; Gallego-Lopez & Essex, 2016; Gencer, 2017; Japan Government, 2018). Ideally, agreements should be set up before an event to support efficient response and recovery operations (NIST, 2020). Hazard and risk information should be made available to the public to support their decision-making (Gencer, 2017).

## Communicate levels of service

To help communities prepare for future events, clear communication of the levels of service expected after a future disaster event is important. This raises awareness of how long communities may have to cope without the services they depend on. This will help communities and critical customers with their resilience/emergency preparedness planning and will establish service expectations (Guenther & Balbus, 2014).

## Leverage disruptive events

Disruptive events provide an opportunity for learning, evaluation, and improvement, to enhance resilience and future planning (Culler et al., 2021; Gencer, 2017; Guenther & Balbus, 2014). Having just experienced a major disruptive event, people are often more receptive to preparedness and resilience initiatives. It is a great opportunity to motivate people and organisations to take actions that will enhance preparedness and awareness for future events.

# Conclusion

It is crucial to understand that resilience is not a fixed destination, but rather an ongoing journey. To truly build resilience, it is important to recognise that planning must be a dynamic and iterative process that continuously adapts to emerging threats and shifting community needs (APA, 2014; Stout et al., 2019). This ensures our infrastructure systems, and the organisations that manage them, stay ahead of potential disruptions.

Building resilience into our critical infrastructure systems involves an awareness of community needs, hazard exposure and service criticality. It involves consideration of both improvements in network design (network redundancy, asset robustness and asset exposure) and emergency preparedness measures (recovery support, stockpiles and back-ups). It involves a robust assessment of resilience benefits for different interventions options. Developing plans to improve resilience involves the engagement of all stakeholders and clear communication between parties.

In today's ever-changing and uncertain world, building resilience into recovery is no longer a choice, but a necessity. By following these principles and continuously striving to improve resilience strategies, we can better withstand and recover from disruptions in the future.

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