

Building infrastructure resilience: a framework for regulatory integration

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ABSTRACT

This paper presents a comprehensive framework for evaluating infrastructure resilience investments across regulated utilities in New Zealand, developed for the Commerce Commission to support integration of resilience principles into regulatory processes. The research addresses electricity lines, gas pipelines, fibre networks, airports, and water infrastructure.

The study establishes that effective infrastructure resilience requires moving beyond traditional asset-hardening approaches to embrace system-wide thinking across four critical dimensions: organisational resilience, information and planning systems, physical system attributes, and investment decision-making processes. This multi-dimensional approach recognises that increasing event frequency and severity, combined with resource constraints, necessitate consideration of diverse resilience-building strategies including temporary service delivery options and enhanced organisational capability.

The framework emphasises evidence-based investment decision-making incorporating multi-hazard risk awareness, infrastructure interdependencies, comprehensive cost-benefit accounting including distributional impacts, and community risk tolerance. Multiple evaluation methodologies are reviewed, including Cost-Benefit Analysis, Multi-Criteria Analysis, Real Options Analysis, and Robust Decision Making, with guidance on framework selection based on uncertainty context and data availability.

A dual measurement approach is proposed: resilience outcomes (evaluating post-disruption performance across asset damage, recovery, and service impacts) and resilience capacity (evaluating forward-looking preparedness through system attributes and organisational capabilities).

The research provides practical pathways for regulatory implementation, balancing resilience improvement with consumer affordability considerations while enabling coordinated, community-aligned resilience planning across New Zealand's infrastructure sectors.

1 INTRODUCTION

Infrastructure systems in New Zealand face an increasingly complex threat landscape. Recent events such as the Canterbury and Kaikōura earthquakes, Auckland Anniversary Day floods, and Cyclone Gabrielle highlight the vulnerability of critical infrastructure to natural hazards. Beyond these acute shocks, infrastructure must also respond to chronic stressors including climate change, demographic shifts, technological disruption, and evolving cyber threats. New Zealand ranks in the top three OECD countries for reported natural hazard damage, with central government spending at least \$33 billion on natural hazards between 2010 and 2025 (New Zealand Infrastructure Commission /Te Waihanga, 2025).

The Commerce Commission (ComCom) regulates utilities across sectors where competition is limited—electricity lines, gas pipelines, telecommunications, airports, and water services. ComCom's mandate is to promote the long-term interests of consumers through efficient, reliable service provision at fair prices. As resilience becomes increasingly integral to infrastructure performance, ComCom could play a role as both gatekeeper and enabler: ensuring utilities invest appropriately in resilience while protecting consumers from excessive costs.

This paper summarises a framework developed for ComCom to support the integration of resilience principles into regulatory processes. The framework draws on over a decade of focused research and practice in infrastructure resilience, incorporating insights from literature review, expert analysis, and case studies across New Zealand's regulated infrastructure sectors.

Note that the framework was developed to inform ComCom and does not necessarily represent the views of ComCom at the time of writing.

2 THE MULTI-DIMENSIONAL NATURE OF RESILIENCE

2.1 Beyond asset hardening

Resilience is often narrowly conceptualised as physical infrastructure robustness - the ability of assets to withstand hazard impacts. However, effective resilience is multi-dimensional, extending beyond asset hardening to encompass service delivery, organisational capacity, and community preparedness (Bruneau et al., 2003; Kwasinski, Kwasinski, & Krishnamurthy, 2024; Rus, Kilar, & Koren, 2018). Historically, physical system improvements such as asset strengthening and network redundancy have been the default mechanism for increasing resilience. While these remain important, increasing frequency and severity of events combined with resource constraints necessitate consideration of a wider range of options.

The National Infrastructure Plan 2015 (National Infrastructure Unit, 2015) identified eight resilience attributes critical to infrastructure performance: service delivery focus, adaptation capacity, community preparedness, clear responsibility frameworks, interdependency management, financial strength, continuous improvement, and organisational performance. These attributes collectively recognise that resilience improvements can be achieved through diverse interventions spanning physical, organisational, and technological domains.

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2.2 Four critical dimensions

Within a utility, four key areas impact resilience outcomes (Figure 1). All these areas need to be considered when designing regulatory approaches, including, in the case of ComCom, price-quality pathways and information disclosure requirements:

Organisational resilience: The capacity of infrastructure operators to effectively plan for and respond to disruptions, including financial health, staff capability, leadership, and business continuity management.

Information and planning systems: The availability of adequate hazard data, risk analysis processes, and investment analysis capabilities to determine appropriate resilience investments.

Physical system attributes: Physical attributes of infrastructure networks that reduce damage during events or enable rapid restoration, including asset robustness, network redundancy, and emergency response provisions.

Investment decision-making: Robust financial decisions based on recognised processes and techniques that ensure financially sound and well-prioritised investments.

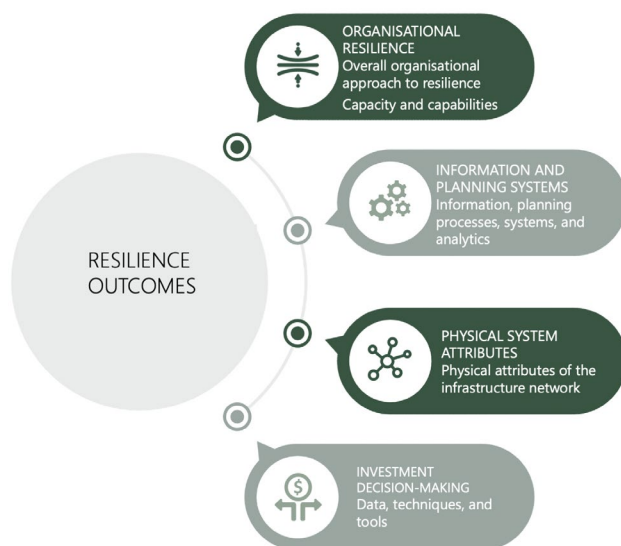


Figure 1 Dimensions affecting infrastructure resilience

2.3 Sectoral context and maturity

Each regulated sector faces unique challenges shaped by hazard exposure, asset vulnerability, market context, and organisational attributes. Understanding these differences is critical when designing regulatory approaches. Table 2 summarises key contextual factors affecting resilience maturity across sectors.

Table 1 Sector context affecting resilience maturity

Sector	Key vulnerabilities	Investment drivers	Resilience maturity	Key resilience considerations
Electricity	Wide geographic exposure; high interdependency impact on other sectors	Growth, renewables transition, asset renewal, extreme weather	Relatively mature; sector guidance available (Electricity Engineers' Association, 2022)	Significant variance of maturity across 29 EDBs; Value of Lost Load well-established for reliability

Telecom	High vulnerability to electricity disruption; complex interconnected networks	Technology upgrades, capacity expansion, modest renewal needs	Mature risk management; developing emergency management plan (TCF)	Reluctance to share asset data can limit coordinated planning
Gas	Dependence on production sources; stranded asset risk from transition	Declining due to electrification; some resilience and renewal investment	Comprehensive adaptation planning (e.g., Powerco 2024 Climate Adaptation & Resilience Plan)	Transition uncertainty complicates long-term resilience planning
Airports	Often on low-lying coastal land; dependent on access, water, fuel, electricity	Safety/security requirements; tourism growth driving capacity expansion	Advanced asset management; emergency response capability focus	Regulated for safety and security by CAA, strong commercial drivers
Water	Very high vulnerability; poor asset condition from under-investment	Massive investment shortfall (\$120-185B)(Pennington, 2021); treatment upgrades, condition improvement	Low asset planning maturity; entering regulatory environment	Opportunity to embed resilience in governance changes and investment prioritisation

3 INVESTMENT DECISION-MAKING FOR RESILIENCE

Robust investment decision-making is fundamental to building infrastructure resilience effectively and efficiently. This section presents principles and frameworks to guide resilience investment evaluation.

3.1 Foundation principles

Twelve principles underpin effective resilience investment decision-making (Figure 1). These principles are grouped into four categories that align with typical risk assessment steps, though significant interconnections exist between them.

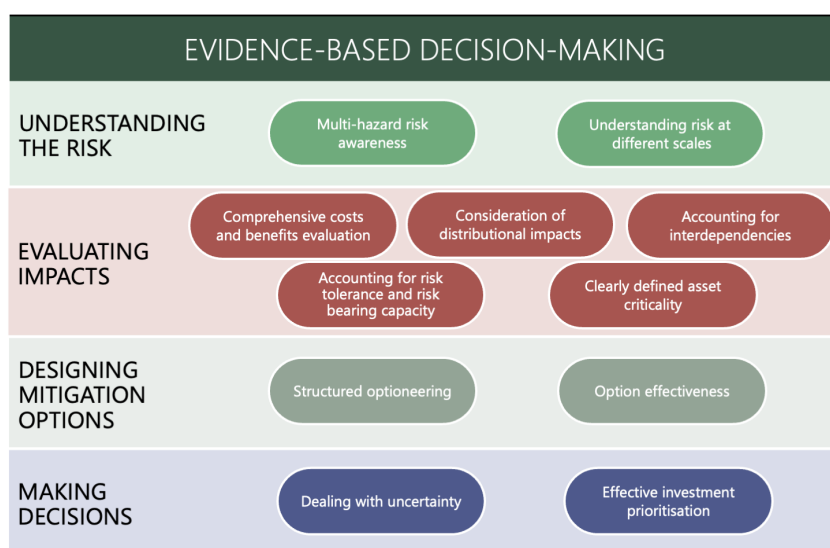


Figure 2 Principles for investment decision-making

Evidence-based decision-making: Valid, fit-for-purpose data and analysis must substantiate investment needs, with confidence levels and data uncertainty explicitly acknowledged. The quality and appropriateness of evidence should match the scale and severity of the risk being addressed.

Multi-hazard risk awareness: Investment decisions must look across hazards, severities, and timeframes rather than focusing on single threats in isolation. This includes considering both acute shocks (earthquakes, floods) and chronic stressors (climate change, demographic shifts), as well as potential cascading and coincident hazards.

Understanding risk at different scales: Hazards and their impacts vary across space, time, and affected populations, requiring analysis at multiple scales. Risk assessments should account for both high-impact low-probability events and low-impact high-probability risks, while recognising that impacts are not experienced uniformly across consumer groups.

Comprehensive costs and benefits: Investment evaluation must identify the full range of impacts across economic, natural, social, and human domains. This includes both direct impacts (asset damage, immediate service loss) and higher-order impacts (supply chain disruptions, ecosystem service interruptions), while avoiding double-counting of stock and flow measures.

Accounting for interdependencies: Modern infrastructure systems are highly interdependent, with disruptions in one system cascading through physical, cyber, geographic, and logical connections to others (Rinaldi, Peerenboom, & Kelly, 2001). Effective resilience investment must consider both infrastructure interdependencies and economic interdependencies, including potential failures in just-in-time supply systems.

Consideration of distributional impacts: Investment decisions should examine effects on different consumer types to ensure existing social inequities are not exacerbated (Grimson, McDonald, McDonald, Monge, & Brown, 2024). Market-based valuations may incorporate wealth-based biases that undervalue impacts on lower-income consumers, requiring careful consideration of equity in both modelling approaches and investment prioritisation.

Risk tolerance and risk-bearing capacity: Community perspectives on acceptable risk levels and desired service standards should inform investment priorities, recognising that different communities have varying needs and expectations. Assessments should capture both what consumers want (risk tolerance) and what they can cope with (risk-bearing capacity), as these are not always aligned (Kilvington, Brown, Horn, & Ross-Donald, 2025).

Clearly defined asset criticality: Understanding the relative importance of infrastructure components, based on their impact if disrupted during both normal operations and emergency response, enables targeted investment prioritisation. Criticality assessments combine physical vulnerability with socio-economic impact to identify where resilience investments will provide greatest benefit (New Zealand Lifelines Council, 2023).

Structured optioneering: Effective investment cases require developing and evaluating a wide range of clearly defined options spanning avoid, control, transfer, and accept strategies. Options should consider co-benefits, climate adaptation, emerging technologies, decentralised solutions, and alternative service delivery methods beyond traditional asset-centric approaches.

Option effectiveness: Options must be evaluated for both cost-effectiveness (benefit-cost ratios) and temporal appropriateness (optimal timing of intervention). Long-term considerations are critical, as initial investment choices constrain future options, and changing conditions (particularly climate change) affect when interventions deliver maximum value.

Investment prioritisation: Strategic sequencing of projects within and across utilities maximises system-wide resilience through coordinated network optimisation. Recognising infrastructure as a system-of-systems allows for efficient project scheduling that accounts for interdependencies and ensures consumers realise full benefits from investments.

Dealing with uncertainty: Investment decisions must acknowledge and manage inherent uncertainties in hazard timing, vulnerability evolution, and behavioural responses to events. Appropriate techniques include sensitivity analysis for well-defined systems, scenario testing for systemic uncertainties, and adaptive planning approaches (real options analysis, dynamic adaptive pathways) for deep uncertainty contexts.

3.2 Decision-making frameworks and tools

Multiple frameworks exist for evaluating resilience investments, each suited to different contexts. Framework selection should reflect the uncertainty context and data availability. The Better Business Case (BBC) framework, based primarily on Cost-Benefit Analysis (CBA), provides best-practice guidance for public infrastructure investment in New Zealand. However, alternative frameworks may be more appropriate depending on the decision context:

- Cost-Benefit Analysis: Quantifies costs and benefits in monetary terms; well-established but sensitive to parameter selection and may inadequately treat intangible values (Boardman, Greenberg, Vining, & Weimer, 2018)
- Multi-Criteria Analysis: Enables stakeholder participation and multi-metric assessment; subjective but valuable when objectives are ambiguous (Dodgson, Spackman, Pearman, & Phillips, 2009; Infrastructure Australia, 2021)
- Real Options Analysis: Values flexibility and adaptive capacity; suitable for dynamic investment contexts (Geltner, Kumar, & Van de Minne, 2021)
- Robust Decision Making: Performs well across multiple futures; appropriate for deep uncertainty (Lempert, Groves, Popper, & Bankes, 2006)
- Dynamic Adaptive Policy Pathways: Maps intervention sequences with trigger points; suitable for climate-sensitive infrastructure (Kwakkel & Haasnoot, 2019)

Supporting these frameworks are various evaluation tools including economic models (Input-Output Analysis, Computable General Equilibrium models, MERIT), risk/catastrophe models, and valuation methods (stated preference, revealed preference, cost-based approaches). Selection depends on the scale and complexity of impacts being assessed.

3.3 Value of Lost Load and its limitations

The Value of Lost Load (VoLL) is an established metric for quantifying the economic cost of service interruptions, particularly in the electricity sector. VoLL represents customers' willingness to pay to avoid outages and can be estimated through proxy methods, survey-based approaches, or revealed preference methods. While VoLL provides valuable monetisation of resilience benefits, important limitations must be considered when applying it to resilience evaluation:

- Consumer representation: Different customer types experience varying impacts; average values may not adequately represent specific affected populations
- Duration scaling: Impacts often do not scale linearly with outage duration; VoLL metrics typically assume linear relationships
- Disruption types: VoLL may not capture the full range of service disruption scenarios, particularly for water infrastructure
- Health and environmental impacts: VoLL may inadequately capture significant public health or environmental consequences
- Higher-order impacts: Cascading effects through interdependent systems may not be fully reflected

For complex, interconnected infrastructure systems and long-duration disruption events, VoLL should be supplemented with other analytical approaches, particularly economy-wide modelling tools like MERIT (www.merit.org.nz) that can capture cascading effects and out-of-equilibrium dynamics.

3.4 Robust business case framework

A robust resilience investment business case integrates the principles and tools described above into a structured evaluation process (Figure 2). This framework could be developed further to support utilities in preparing investment cases and to support regulators like ComCom in evaluating the sufficiency and quality of business cases submitted through customised price paths.

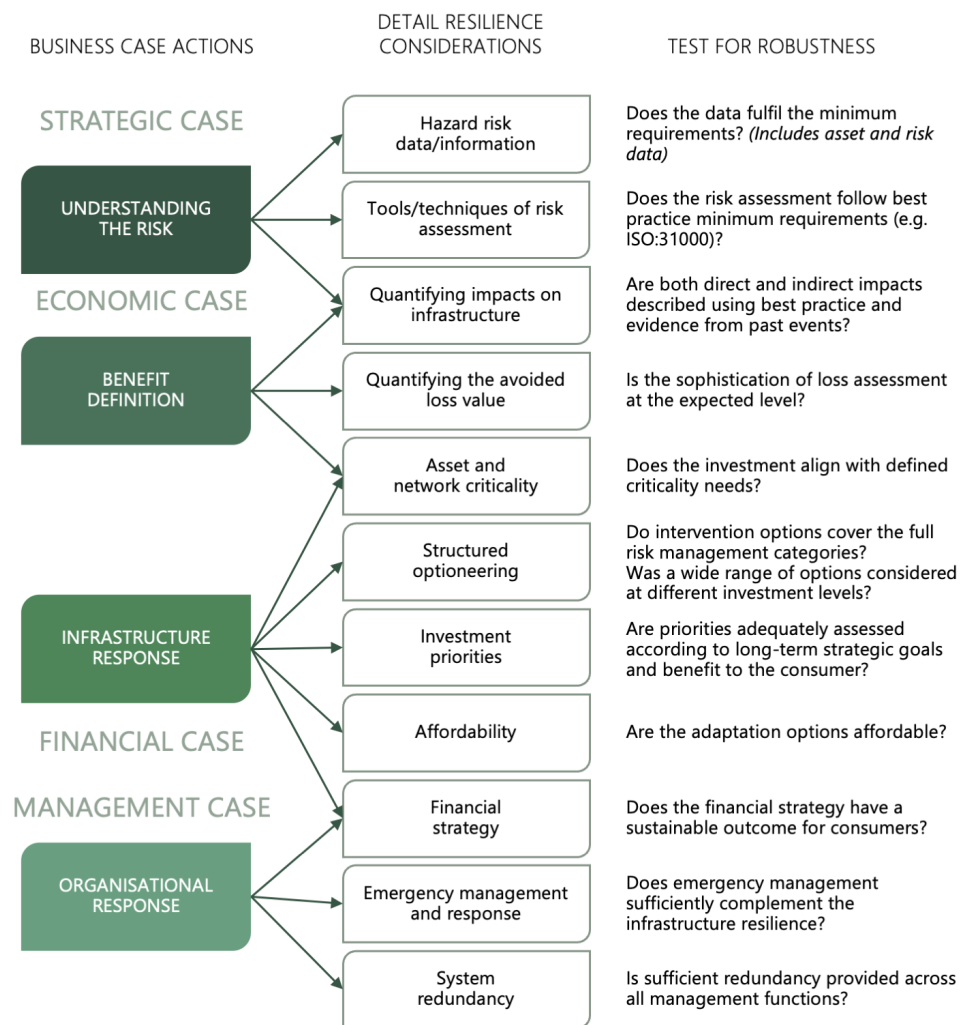


Figure 3 Robust business case framework

4 MEASURING RESILIENCE

Complementing robust investment decision-making, effective resilience measurement provides accountability and enables tracking of improvement over time. This section presents a dual approach to resilience measurement: evaluating actual post-disruption performance (resilience outcomes) and forward-looking preparedness (resilience capacity).

4.1 Resilience outcomes

Resilience outcomes evaluate actual performance following disruption events across three dimensions (Figure 3):

- **Asset damage:** Amount of damage experienced, measuring network robustness through cost to repair and degree of damage
- **Asset performance and recovery:** How quickly service can be returned, measured through efficiency, operational performance, and restoration timelines
- **Service loss:** Impact of disruption on consumers, including quantity of affected customers and quality of service degradation

These indicators and associated metrics could be used post-event to measure actual performance or pre-event through modelling to estimate expected impacts under various scenarios. Unlike reliability measures (e.g. SAIDI/SAIFI), resilience outcomes are highly dependent on event characteristics and community expectations / business-as-usual levels of service, making it difficult to set universal minimum service standards. They are better suited to information disclosure requirements that enable performance comparison over time and across similar events.

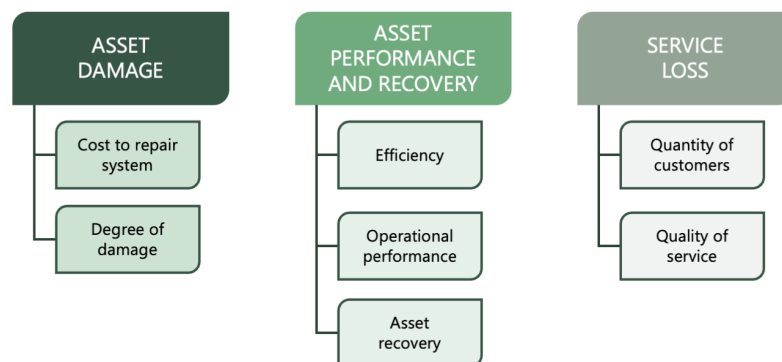


Figure 4 Resilience outcomes indicators

4.2 Resilience capacity

Resilience capacity evaluates forward-looking preparedness across three critical dimensions: physical system attributes, organisational resilience, and information and planning systems (Figure 4).

Physical system attributes

These relate to network condition as an indicator of likely post-event damage and function:

- **Robustness:** Capacity of assets to withstand hazard impacts
- **Redundancy:** Diversity in distribution and supply
- **Emergency provisions:** Temporary service delivery options and spare parts

Organisational resilience

The capacity of infrastructure operators to plan for and respond to disruptions:

- **Financial health:** Capacity to bear losses and fund response/recovery
- **Staff capacity:** Trained personnel, surge capability, situational awareness
- **Leadership and culture:** Decision-making, innovation, staff engagement
- **Networks and relationships:** CDEM engagement, sector collaboration
- **Disruption readiness:** Quality of business continuity plans

Information and planning systems

The capacity to understand threats and plan effectively:

- Hazard/exposure data: Use and sufficiency of threat information
- Asset information: Quality and completeness of asset data
- Risk assessment tools: Quality of analytical capabilities
- Emergency management systems: Fault identification and operations readiness
- Customer understanding: Critical customer identification and needs assessment
- Interdependency awareness: Upstream and downstream dependencies

Resilience capacity measures could be evaluated through self-assessments, third-party audits, or modelled predictions. Several tools already exist to support evaluation, including the Electricity Engineers' Association's Resilience Management Maturity Assessment Tool and the UN Office for Disaster Risk Reduction's Resilience Maturity Assessment framework.

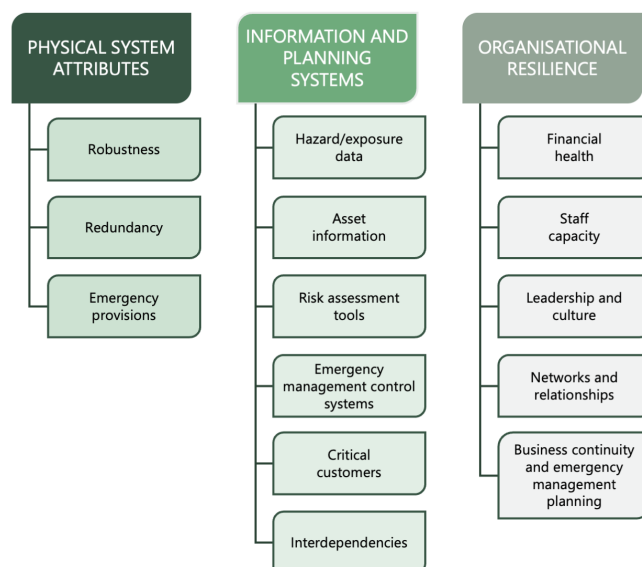


Figure 5 Resilience capacity indicators

5 CONCLUSIONS

Building infrastructure resilience in New Zealand requires moving beyond traditional asset-centric engineering approaches to embrace system-wide thinking that puts consumers and service-delivery at the centre. To do this utilities need to focus on building organisational resilience, information and planning systems, physical system attributes, and investment decision-making capability (Figure 1). Each dimension offers opportunities for resilience improvement, recognising that asset hardening represents just one pathway among many.

The diversity of New Zealand's regulated infrastructure sectors - spanning maturity levels, hazard exposure, market contexts, and organisational capabilities - demands flexible regulatory approaches. Water infrastructure, entering a new regulatory environment with massive investment needs, presents particular opportunity to embed resilience from the outset. More mature sectors like electricity and telecommunications can focus on coordinated planning and information sharing to maximise collective resilience benefits.

Regulators, like ComCom, have significant opportunity to guide utilities on a continuous resilience improvement journey. Potential actions span guidance development, maturity assessment tools, information disclosure requirements, and support for community-aligned planning. Critically, all approaches must

balance resilience improvement with consumer affordability, recognising that over-investment can harm consumers as much as under-investment.

By embracing system-wide thinking and evidence-based evaluation, New Zealand can build infrastructure resilience that serves consumer interests, supports economic prosperity, and enhances community wellbeing in an increasingly uncertain future.

6 ACKNOWLEDGEMENTS

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