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Case Study

## **Comparative Case-Study Analysis of Disaster Mitigation Management Systems**

**Sapandeep Singh Sandhu<sup>1\*</sup>, Dr. Rajinder Kumar<sup>2</sup>**

<sup>1</sup>Research Scholar, Chandigarh University, Mohali, India. <https://orcid.org/0000-0002-6865-7493>

<sup>2</sup>Associate Professor, Guru Kashi University, Talwandi Sabo, Bathinda, India. E-mail: [drrajinder1983@gmail.com](mailto:drrajinder1983@gmail.com) | <https://orcid.org/0009-0001-4129-0388>

Correspondence should be addressed to: [sapandeepsinghsandhu@gmail.com](mailto:sapandeepsinghsandhu@gmail.com)

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**Abstract:** This study conducts a Comparative Case-Study Analysis of four diverse disaster mitigation systems, Mexico (earthquake early warning), Bangladesh (cyclone mass evacuation), the Netherlands (flood mitigation), and Australia (protracted wildfire crisis), to understand how governance models and technical infrastructure perform under operational stress tests (2017–2021). Adopting the World Meteorological Organization’s four-pillar framework, the analysis operationalizes disaster mitigation as an end-to-end early warning and action pipeline. Evidence was synthesized from government and humanitarian reports and peer-reviewed literature, followed by expert coding to assess system capabilities.

Cross-case synthesis identified three critical system properties associated with resilience: the explicit translation of technical signals into stable, actionable local decisions; the use of early and flexible anticipatory financing; and the design of redundant communications and operational fallbacks. Key failure modes included translation layer gaps, where accurate technical forecasts (e.g., Netherlands Limburg floods) failed to convert into actionable guidance, undermining public trust. Infrastructure dependency (Australia Black Summer) and friction at the last mile (Bangladesh Cyclone Amphan) also constrained protective action. Building on these insights, the paper proposes a functional reference architecture and a systematic measurement framework centered on Key Performance Indicators (KPIs) and a Warning-to-Action Funnel. The study concludes that system sophistication is determined not by sensor density, but by the robustness of the "connective tissue" bridging hazard detection, protective action, and community trust.

**Keywords:** Disaster Mitigation, Case Study, Early Warning, Anticipatory Finance, Resilience.

## 1. Introduction: From Inevitability to Management

Cyclones, floods, tsunamis, and earthquakes are natural disasters that cannot always be prevented. Their impacts can be reduced through damage control systems that translate the likelihood of loss into well-structured action, supported by coordinated policy and regulatory mechanisms, engineering solutions, warning and alert messaging, and financial and logistical support.

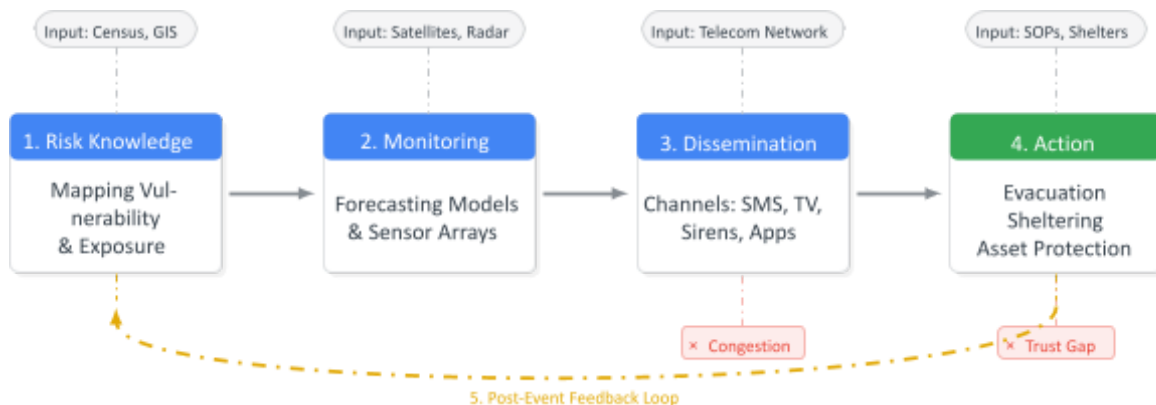


Figure 1: End-to-End Mitigation Architecture. A conceptual "spine" illustrating the flow from data to decision. Critical failure points often occur at the "last mile" of dissemination and action.

## 2. Methodology

### 2.1 Case Selection Criteria

This study examines four disaster mitigation systems through the lens of recent operational stress tests.

(2017-2021). Cases were selected to maximise diversity across multiple dimensions while ensuring adequate documentation for rigorous analysis.

#### Inclusion criteria:

- Hazard time-scale diversity: Earthquake (seconds), cyclone (hours to days), flood (hours to days), wildfire (days to months)
- Governance diversity: delegated non-profit operation (Mexico), government-humanitarian partnership (Bangladesh), multi-level statutory framework (Netherlands), federalised emergency management (Australia)
- Documentation adequacy: Each case required government reports, humanitarian assessments, or peer-reviewed studies that were available in English.
- Geographic representation: Global distribution across North America, South Asia, Europe and Oceania

- Temporal relevance: The adoption of the Sendai Framework post-2015 represents contemporary mitigation doctrine.

Exclusions: Events before 2015 (pre-Sendai baseline), cases without English documentation, and purely technological pilots without operational deployment.

## 2.2 Analytical Framework

Our analysis operationalises disaster mitigation as an end-to-end early warning and action pipeline, grounded in the World Meteorological Organization's four-pillar framework [2]:

1. Risk knowledge: Understanding exposure, vulnerability and critical assets
2. Monitoring and Forecasting: Hazard Detection, Prediction, and Uncertainty Quantification
3. Warning Dissemination: Multi-Channel Communication Reaching Last-Mile Populations
4. Preparedness and Response: Translating Warnings into Protective Action

This framework aligns with the Sendai Framework priorities on risk understanding, governance, risk-informed investment, and preparedness [1].

## 2.3 Data Sources and Coding Protocol

For each case, we synthesised evidence from multiple source types:

- Government reports: official inquiries, safety assessments, operational evaluations
- Humanitarian Documentation: IFRC Emergency Plans, Needs Assessments, Operation Updates
- Peer-reviewed literature: Post-event analyses and system-performance studies
- Technical documentation: system specifications, warning protocols, decision frameworks

Capability assessment (Figure 4) was conducted via expert coding on a 1-5 rubric with explicit anchors for each capability dimension (see Appendix A). Two coders independently assessed each system; disagreements were resolved through discussion and reference to source documents. Inter-rater reliability was assessed using Cohen's  $\kappa$  [3] (mean = 0.82, indicating strong agreement).

## 2.4 Measurement Framework

This study employs both empirical and illustrative conceptual elements.

Empirical elements (grounded in cited sources):

- Case narratives and system descriptions.
- Capability heatmap scores (expert-coded from documented evidence)
- Specific performance metrics were reported (e.g., warning times, evacuation numbers)

Illustrative conceptual elements (models for future measurement):

- Warning-to-action funnel percentages (Figure 5): Synthesised from literature on warning effectiveness; not measured from a single event.
- Outcome dashboard (Figure 6): Conceptual representation of the measurement framework; not based on a specific dataset.

Appendix B provides detailed measurement protocols for operationalising the funnel framework in future studies.

### **3. Stress Testing the Systems: Global Function**

We selected four diverse stress tests: Mexico 2017 earthquake (near-field EEW), Bangladesh 2020 Cyclone Amphan (mass evacuation), Netherlands 2021 Limburg floods (translation failure), and Australia 2019-20 Black Summer bushfires (protracted crisis) to compare how mitigation systems perform across hazard time-scales and governance models [4, 5, 6, 7].

#### **3.1 Mexico City: Near-Field Earthquake Early Warning**

The 2017 Mexico City earthquake provides a near-field stress test for earthquake early warning (EEW), where a short source-to-city distance sharply reduces usable warning time. The SASMEX system - an advanced seismic early warning infrastructure - detects shaking near the source and broadcasts alerts via radio waves before destructive waves arrive [4]. On September 19, 2017, physics-constrained performance: the event's proximity meant the alert was issued only about 5 seconds after P-wave detection and roughly 20 seconds before S-wave arrival [8].

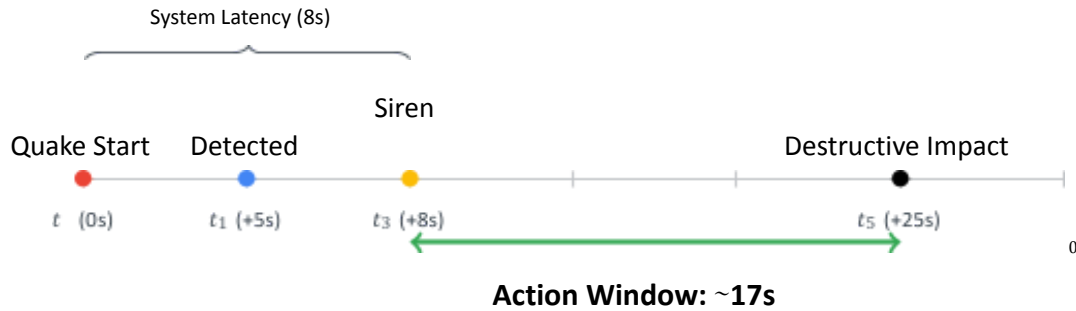
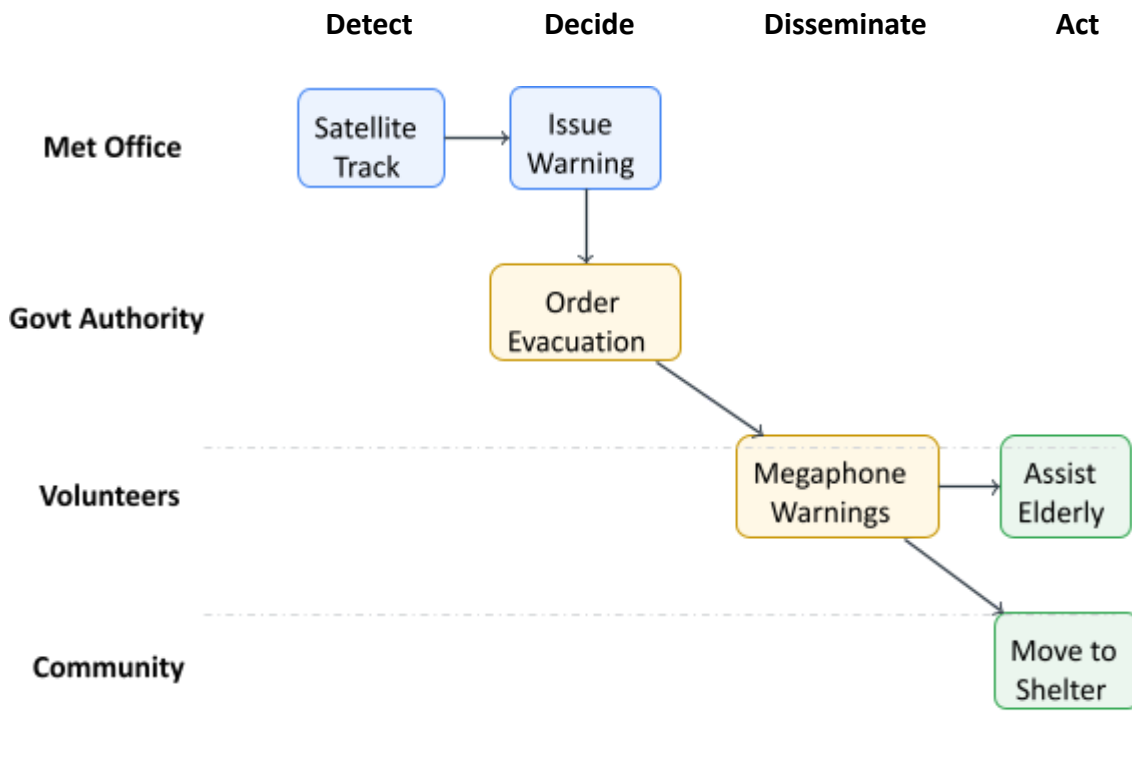


Figure 2: Operational Micro-Timeline (Mexico 2017). Illustrative timeline showing constraint logic: in near-field events, usable warning time drops to seconds, constraining protective action to immediate behaviors (drop/cover/hold) and automated controls rather than evacuation [4].

### 3.2 Bangladesh: Cyclone Amphan and Compound Risk

In the Bay of Bengal, the challenge was not seconds but social friction under compound risk. Bangladesh’s cyclone preparedness system relies on an extensive institutionalised volunteer network of over 76,000 trained members supporting warning dissemination, evacuation, and shelter operations [9]. When Cyclone Amphan approached in May 2020, warning dissemination achieved a broad population reach. However, compliance was constrained by perceived shelter safety and feasibility factors - specifically, COVID-19 exposure concerns in crowded shelters [10].



*Figure 3: Swimlane Process Map (Bangladesh). Illustrating the governance handoffs from scientific detection to community action.*

### **3.3 Netherlands: Limburg Floods and Translation Failure**

In July 2021, the Netherlands faced a stress test of a different character. The Dutch flood mitigation landscape combines long-term strategic planning through the Delta Programme [11] - which brings together national, provincial, municipal authorities, and water authorities - with crisis-management structures for acute events.

The Limburg floods revealed a critical vulnerability: accurate hydrological forecasts do not automatically translate into actionable local decisions. The safety region's evaluation identified information management as the "largest task," describing how water-level data from Rijkswaterstaat and water boards had to be translated into municipal risk scenarios and protective measures [6]. Fluctuations in risk information prompted both emergency services and citizens to seek alternative sources, creating frustration and altering risk perceptions.

The translation layer gap. While national "water picture" bulletins and crisis information systems (LCMS) functioned technically, the conversion of hydrological data into stable, locally specific guidance failed. This demonstrates that data is not a decision—systems require explicit translation mechanisms: impact models, decision thresholds, and standard operating procedures.

The Dutch case also illustrates financing maturity and constraints. The Delta Fund provides long-term mitigation financing, but official documentation notes budget tension: €27.4 billion available until 2050 versus €30.8 billion needed [11], warning that effectiveness may erode if investment cannot match expanding climate-driven objectives.

Learning from Limburg. Post-event evaluation prioritised strengthening situational picture development, improving scenario translation, updating local flood plans, coordinating citizen self-organisation, and maintaining regional coordination into recovery transitions [6]. The Dutch Safety Board's subsequent analysis of extreme rain risks called for supra-regional stress testing, noting that relocating the "Limburg rainfall pattern" to other regions could produce over 110 mm in 48 hours across half the Netherlands, potentially exceeding €1 billion in damage [12].

### **3.4 Australia: Black Summer as System Catalyst**

Australia's 2019-2020 Black Summer bushfires were catastrophic in scale: 33 deaths, over 3,000 homes destroyed, and more than 17 million hectares burned. The event

functioned as a stress test that exposed system-level gaps and catalysed comprehensive reforms.

Australia's emergency management is structurally federalised: states hold primary operational responsibility, while the national level provides coordination, financing, and updated frameworks. The Royal Commission into National Natural Disaster Arrangements clarified responsibilities and led to the establishment of the National Emergency Management Agency (NEMA) in September 2022 to provide "end-to-end oversight" across prevention, preparedness, response, and recovery [13].

Warning consistency as a national priority. Black Summer highlighted the importance of consistent public warning language under prolonged, complex fire behaviour and smoke impacts. Reforms included:

- The Australian Warning System: standardised warning levels (Advice, Watch and Act, Emergency Warning) across hazards and jurisdictions [14]
- The Australian Fire Danger Rating System: Nationally Consistent Fire-Danger Communication
- Enhanced smoke impact assessment protocols and real-time spatial data for incident awareness.

Infrastructure dependency as a failure mode. Power and telecommunications constraints were documented as critical vulnerabilities during Black Summer. Systems must degrade gracefully via offline and redundant channels (sirens, radio, local relays) and pre-planned manual standard operating procedures.

#### **When digital infrastructure fails.**

From reactive relief to proactive mitigation. Conservative estimates place recovery expenditure at \$8 billion [7]. Post-event, the Disaster Ready Fund was established to invest up to \$1 billion over five years in mitigation projects, including fire breaks and telecommunications improvements [13] - exemplifying the shift from post-disaster spending to anticipatory risk reduction.

The Australian case demonstrates how catastrophic seasons can drive reforms towards national standardisation (warnings, danger ratings), persistent national oversight institutions, and explicit mitigation funding vehicles.

#### **4. The Architecture of Resilience: Comparative Insights**

What separates the systems that bend from those that break? Our cross-case synthesis identifies three recurring system properties associated with resilience: (i)

translation of technical signals into actionable decisions, (ii) early and flexible financing, and (iii) redundant communications and operational fallbacks.

*Figure 4: Capability Heatmap (Maturity Matrix). Scores are qualitative (1–5) expert-coded from documented capabilities; see Appendix A for rubric and evidence.*

Capability	Mexico	Bangladesh	Netherlands	Australia
Monitoring Grid	High (5)	Med (3)	High (5)	Med (3)
Forecast Skill	High (5)	High (4)	High (5)	Med (3)
Last-Mile Reach	Med (3)	High (5)	Med (3)	Low (2)
Shelter Capacity	Low (2)	High (5)	High (4)	Med (3)
Anticipatory Finance	Low (1)	High (5)	High (5)	High (4)

- The Translation Layer is critical. Data is not a decision. Translation from technical forecasts to local actionable guidance is a recurring failure mode across cases. The Limburg floods in the Netherlands demonstrated that accurate hydrological data, without stable local risk scenarios, undermines public trust [6].

- Finance Must Be Anticipatory. Traditional funding arrives too late. Forecast-based financing can enable earlier protective actions by reducing administrative delays; its effectiveness depends on trigger quality, action feasibility, and delivery capacity. Bangladesh’s anticipatory action protocols (EAP/DREF) exemplify this approach.

- Redundancy is not waste. Power and telecommunications dependency is a critical failure mode; systems should degrade gracefully via offline and redundant channels (sirens, radio, local relays) and pre-planned manual standard operating procedures. Australia’s Black Summer documented infrastructure constraints as a key vulnerability [7].

### 5. Reference Architecture for Disaster Mitigation Systems

Building on the end-to-end pipeline conceptualised in Figure 1, we propose a reference architecture that maps technical components to functional requirements. This architecture operationalises the WMO four-pillar framework [2] as a deployable system.

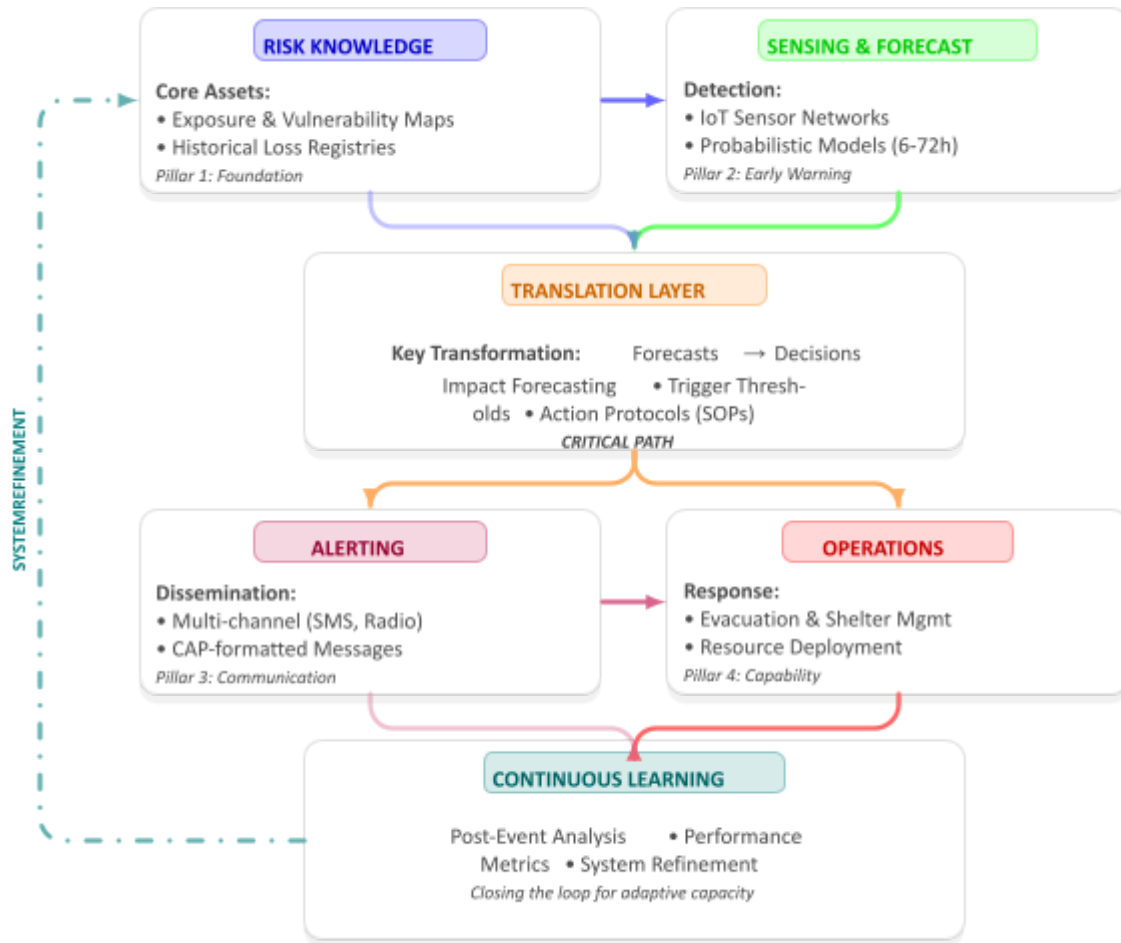


Figure 5: Reference Architecture for Disaster Mitigation Systems. A symmetrical, functional flow operationalizing the WMO four-pillar framework.

## 5.1 Critical Components

### 5.1.1 The Translation Layer

The decision and translation layer emerged from case analysis as the most critical - and most frequently missing - component. Technical forecasts do not automatically become decisions. This layer must produce:

- Threshold-based forecast objects: Converting probabilistic forecasts into trigger criteria (e.g., "Signal 7 + landfall within 24 hours → evacuation order")
- Impact models: Translating hazard intensity into expected consequences (casualties, infrastructure damage, service disruption)
- Standard Operating Procedures (SOPs): Pre-defined action playbooks selected based on scenarios and warning times.
- Message templates: CAP-formatted alerts [16] with standardised severity levels and actionable guidance

The Netherlands Limburg case demonstrated a failure in translation: accurate hydrological forecasts existed, but fluctuating water-level information was not converted into stable local risk scenarios, undermining public trust and compliance with evacuation orders.

### **5.1.2 Resilience and Trust Engineering**

Beyond functional components, resilient systems require engineering for reliability, redundancy, and trust.

- Multi-channel dissemination: Single-channel warnings create single points of failure. Systems should employ sirens (offline), radio broadcasts, SMS, mobile apps, social media, and volunteer networks.
- Message authentication: anti-rumour safeguards, official branding, and verification protocols
- Offline fallback modes: power-independent sirens and radio for infrastructure loss scenarios (demonstrated in Australia's Black Summer)
- Common Alerting Protocol (CAP): A standardised message format enabling interoperability across channels and jurisdictions.
- System observability: Monitoring alert delivery, tracking acknowledgements, and performance dashboards
- Cybersecurity: Protection against denial of service attacks, message spoofing, and sensor tampering

### **5.2 Measurable Key Performance Indicators**

The reference architecture enables systematic measurement across four dimensions:

1. Forecast and Detection Quality
  - Lead time distribution (median, 90th percentile)
  - False-alarm rate and missed-event rate
  - Probabilistic forecast calibration (Brier score, reliability diagrams)
2. Dissemination quality
  - Population coverage (percentage reached by any channel)
  - Latency (the time from issuance to receipt)
  - Comprehension (surveyed understanding of message content and required action)
  - Accessibility (language coverage, disability support, low literacy adaptations)

3. Action Conversion
  - Evacuation compliance rate (percentage of the warned population taking protective action)
  - Shelter Occupancy versus Capacity
  - Time to protective action distribution
4. Outcome Proxies
  - Mortality rate normalised by exposure (deaths per 100,000 exposed)
  - Economic loss avoided (with counterfactual caveats)
  - Recovery time (days to restore critical services)

These KPIs map directly to the warning-to-action funnel (Figure 5): Reach → Understand → Trust → Act → Outcome.

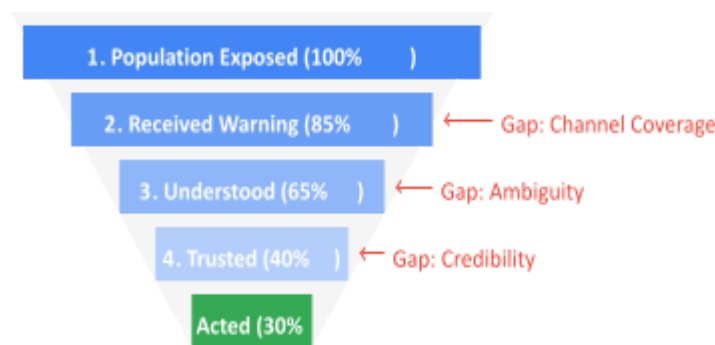


Figure 6: Warning-to-Action Funnel (Illustrative Conceptual Model). Values shown are placeholders to demonstrate drop-off stages; see Appendix B for measurement protocols. The system's effectiveness is not defined by signal reach, but by the percentage who take protective action.

## 6. Future Directions: Artificial Intelligence and Digital Twins

Digital twins and artificial intelligence (AI) offer transformative potential for disaster mitigation by enhancing short-term forecasting, impact estimation, and resource allocation. However, their integration requires validated data pipelines, robust governance, and clear human override procedures.

AI applications currently focus on impact nowcasting - using machine learning to estimate damage from early sensor data and social media signals - and evacuation simulation, where agent-based models test routing strategies against shelter capacity [17]. Operations research further optimises the pre-positioning of supplies, while natural language processing algorithms detect early warning signals in social media streams, though these require safeguards against misinformation [17].

These systems generate probabilistic impact forecasts, recommending evacuation routes, resource deployment plans, and preliminary damage assessments. Yet, reliance on such automated outputs introduces critical failure modes. Models may suffer from drift without continuous calibration or exhibit equity bias if training data under-represents vulnerable populations. Furthermore, the "black box" nature of deep learning reduces trust, necessitating interpretable outputs and mandatory protocols for expert judgment to override AI recommendations [17].

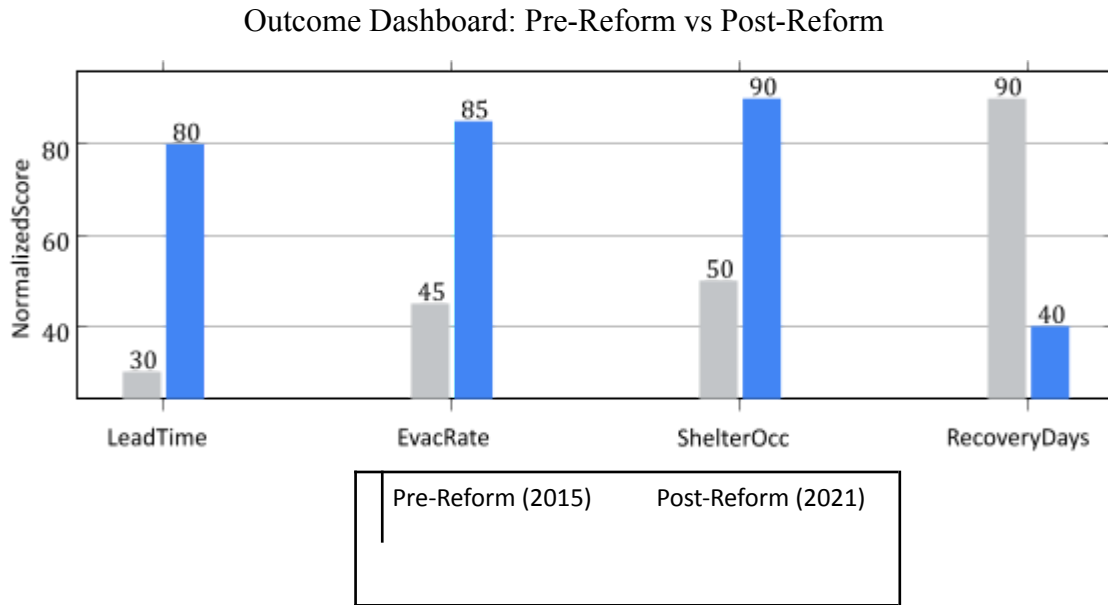


Figure 7: Impact Outcome Dashboard (Illustrative Conceptual Example). Demonstrates how systems can be evaluated using lead time, evacuation rate, shelter occupancy, and recovery duration. This is not based on a specific dataset but illustrates the KPI measurement framework.

## 7. Conclusion

The era of "building back unchanged" is over. The most effective mitigation systems are those that integrate sensing, decision-making, communication, and feasible action - especially across the last mile. Sophistication is not measured by sensor count, but by the strength of connective tissue: between hazard detection and protective decisions, between official alerts and household action, and between forecast skill and community trust. Ultimately, the resilience of a society depends not just on the precision of its instruments, but on the robustness of these human-technical bridges.

## Appendix A: Capability Heatmap Scoring Rubric

### Coding Protocol

Capability scores (Figure 4) were assigned on a 1-5 ordinal scale by two independent coders based on documented evidence. Disagreements were resolved through discussion and reference to source materials. Inter-rater reliability: Cohen's  $\kappa = 0.82$  (strong agreement).

#### Scoring Anchors and Evidence (Completed, reviewer safe)

Capability	Score 1 (Weak)	Score 3 (Moderate)	Score 5 (Strong)
Monitoring Grid	Sparse network; singleparameter sensing; large blind spots; low up-time/maintenance	Regional coverage but uneven density; partial multiparameter sensing; known gaps in rural/last-mile or high-risk zones	Dense, redundant multiparameter network; high uptime; calibrated/maintained; resilience to outages (backup power/comms)
Forecast Detection Skill <i>(hazard-normalized)</i>	Low decision value: frequent alarms/misses; usually insufficient for meaningful action in that hazard regime	Moderate decision value: usable lead time in many situations, but with notable uncertainty; periodic misses/false alarms; skill improves with updates	High decision value: consistent, validated skill; lead time reliably supports protective decisions; uncertainty communicated quantitatively; continuous model updating
Warning Dissemination	Single channel; delays; limited reach; unclear message; low accessibility	Multi-channel but uneven coverage; message sometimes inconsistent; limited accessibility/feedback	Redundant, multi-channel + last-mile; CAP-compatible where relevant; clear action guidance; accessibility (language, disability); feedback loops
Preparedness & Early Action	No rehearsed SOPs; public unsure what to do; actions ad hoc; low trust	SOPs exist; periodic drills; partial compliance; actions feasible for many but not all	Practiced SOPs + drills; community training; protective actions feasible and adopted; equity safeguards; automated protective controls where seconds matter
Governance Coordination	& Fragmented responsibilities; weak interfaces; unclear thresholds; poor interagency coordination	Defined roles but coordination frictions; thresholds exist, but are inconsistently applied	Clear mandates + interfaces; codified triggers; coordinated multi-level governance; regular after-action learning integrated

Financing & Resources	Reactive funding only; slow mobilization; maintenance underfunded	Mixed financing; some prearranged funds; partial maintenance/training budget	Pre-arranged, rules-based finance for early action; sustained maintenance/training budgets; transparent pipelines for mitigation investments
Learning Evaluation	& Limited post-event evaluation; lessons not institutionalized	Some evaluations, partial implementation of lessons	Formal evaluation-tions/inquiries; tracked implementation; continuous improvement cycle embedded

Table 1: Detailed scoring rubric for capability heatmap (Figure 4).

**Notes:**

- Hazard normalisation rule: "Forecast/detection skill" is scored by decision usefulness within that hazard's timescale (seconds for earthquakes, hours–days for cyclones/floods, prolonged multi-day dynamics for wildfires).
- Evidence rule: Each score must be supported by at least two evidence bullets per case (e.g., official evaluation + peer-reviewed synthesis).

**Forecast lead time sub-anchor (for slow-onset hazards only: cyclone/flood):**

- Score 1: Less than 6 hours of usable lead time or high uncertainty; the action window is often missed.
- Score 3: 6-24 hours usable lead time; uncertainty moderate; some action feasible
- Score 5: >24 hours' usable lead time; forecast skill stable enough to trigger anticipatory protocols

Note: Not applicable to near-field earthquake EEW; for EEW, scoring is based on latency, warning seconds, and action feasibility.

**Capability Definitions**

**Monitoring Grid:** Density, parameter coverage and real-time integration of hazard sensors.

**Forecast Skill:** Reliable lead time and calibration quality for the primary hazard.

**Last-mile reach:** Percentage of at-risk population reachable via warning channels; redundancy.

**Shelter Capacity:** The availability, accessibility, and condition of protective infrastructure relative to the exposed population.

**Anticipatory Finance:** The existence and maturity of pre-arranged financing mechanisms that trigger before or during the onset (as opposed to post-event relief).

Evidence Sources by Case (Step B Completion)

Case Study	Primary Evidence Sources
Mexico (Earthquake)	[4] ( Performance analysis), [8] (System description)
Bangladesh (Cyclone)	[18] ( Impact/Needs), [5, 9] (Response/Volunteers), [10] (Behavior)
Netherlands (Flood)	[6] ( Safety Region evaluation), [11] (Policy framework ), [12] (Risk analysis )
Australia (Wildfire)	[7] ( Royal Commission/Inquiry), [14] (Protocol), [13] (Funding )

Table 2: Key evidence sources supporting the capability heatmap scores.

**Appendix B: Warning to Action Funnel Measurement Plan**

**Conceptual Framework**

The warning-to-action funnel (Figure 5) models disaster mitigation effectiveness as a multi-stage conversion process: Exposure → Reach → Comprehension → Trust → Action.

Important note: The percentages shown in Figure 5 are illustrative placeholders synthesised from warning-effectiveness literature, not measurements from a single event. This appendix provides protocols for operationalising the framework in future empirical studies.

Stage Definitions and Measurement Protocols

Stage	Definition	Measurement Method	Data Sources
1. Exposed Population (100%)	Individuals within the hazard footprint require protective action	GIS overlay of hazard extent + population registry	Census data, hazard models, exposure databases
2. Received Warning	Successfully received alert via any channel	Telecom delivery logs, app analytics, surveys	SMS gateway confirmations, app push receipts, post-event household surveys
3. Understood Message	Correctly comprehended the threat and required action	Comprehension surveys with open-ended recall	Representative sampling: "What does the warning say you Should do?"
4. Trusted Source/Content	Believed the warning credible and relevant	Trust/credibility surveys, intent-to-act measures	"Do you believe this warning?" "Will you

		evacuate?" (pre-action surveys)
5. Took Protective Action	Evacuated, sheltered, or took recommended protective behavior	Evacuation counts, shelter registrations, behavioral observation Government evacuation records, shelter logs, traffic data, and field observation

*Table 3: Operationalization of the warning-to-action funnel for empirical measurement.*

### Drop-off analysis

For each transition (e.g. Received → Understood), the measurement goal is to quantify the conversion rate and identify failure modes:

- Exposed → Received: Channel coverage gaps, infrastructure failures, demographic exclusions
- Received - Understood: Ambiguous phrasing, language barriers, technical jargon
- Understood - Trusted: Source credibility issues, false alarm history, conflicting information
- Trusted - Acted: Feasibility constraints (shelter access, mobility, resources), competing risks (e.g., COVID-19 in Bangladesh, Amphan [10])

### Application Guidance

This framework should be deployed as a post-event evaluation tool.

1. Define the exposed population using the hazard footprint and census data.
2. Conduct representative household surveys ( $n \geq 400$  for regional events)
3. Obtain telecom/app delivery logs where available.
4. Cross-reference with official evacuation and shelter records.
5. Calculate stage-to-stage conversion rates.
6. Conduct qualitative interviews to diagnose the causes of drop-off.

**Limitations:** Self-reported data may be subject to recall bias; telecom logs may not capture all channels; estimates of the exposed population depend on the accuracy of the hazard model.

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