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Strengthening Health Security against Climate-Driven Health Emergencies: Integrating Environmental Surveillance, Disaster Epidemiology, and Health-System Resilience

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ABSTRACT: Climate change is increasing the frequency, intensity, and compounding of health emergencies, including heatwaves, floods, wildfires, storms, and climate-sensitive infectious disease outbreaks. Yet environmental surveillance, disaster epidemiology, and health-system preparedness are still commonly developed in separate institutional silos. This narrative review synthesizes peer-reviewed and institutional literature published between 2017 and 2024 to examine how these three domains can be integrated to strengthen health security. We summarize major hazard–health pathways, appraise environmental and wastewater surveillance, remote sensing, and One Health approaches, and review disaster epidemiology methods for measuring mortality, morbidity, and mental health burden. We then link these functions to health-system resilience capacities. An integrated framework is proposed, connecting hazard detection, risk interpretation, response, and learning. Persistent gaps include data fragmentation, weak subnational capacity, inequity, and limited evaluation. Evidence from global assessments and major

recent events is considered. Priorities for policy, practice, and research are outlined to support equitable, evidence-informed preparedness.

1. INTRODUCTION

Climate change has become a defining determinant of population health and, increasingly, of national and global health security. The 2023 report of the Lancet Countdown documented record-level indicators of heat exposure, extreme weather, food insecurity, and infectious disease transmission suitability, while adaptation in the health sector remained uneven and under-financed (Romanello et al., 2023). The preceding report had already characterized continued dependence on fossil fuels as a driver of escalating health threats (Romanello et al., 2022). The Intergovernmental Panel on Climate Change concluded with high confidence that climate hazards were already causing widespread adverse impacts on human health and well-being, and that risks would intensify with each increment of warming (Change, 2022). An overview of systematic reviews similarly found consistent associations between climate hazards and adverse outcomes spanning mortality, infectious disease, injury, and mental health, with vulnerable groups bearing a disproportionate burden (Rocque et al., 2021).

Health security has traditionally been organized around epidemic-prone pathogens and the core capacities required by the International Health Regulations. Analyses of annual reporting by 182 countries showed substantial variation in these capacities, with many settings reporting limited readiness for the broad range of hazards the regulations cover (Kandel et al., 2020). Climate-driven emergencies challenge this pathogen-centred paradigm in several ways. They arise from physical and ecological processes that are monitored by non-health sectors, they unfold over timescales ranging from hours (flash floods) to decades (shifting vector ranges), and they frequently compound one another, as when a heatwave coincides with wildfire smoke or a cyclone follows a drought. The Global Assessment Report on Disaster Risk Reduction emphasized that risk is increasingly systemic, with cascading effects across sectors that conventional single-hazard planning does not capture (Amaratunga et al., 2023).

Three bodies of practice are central to managing these threats. Environmental surveillance continuously observes meteorological, hydrological, ecological, and pollution conditions, and increasingly pathogen signals in wastewater and the environment, to detect hazards and anticipate health risks. Disaster epidemiology applies epidemiological methods to measure the health effects of hazards, to guide rapid response, and to evaluate outcomes. Health-system resilience describes the capacity of health institutions and actors to prepare for, absorb, adapt to, and recover from shocks while maintaining essential functions (Kruk et al., 2017; Blanchet et al., 2017). Although the World Health Organization has articulated frameworks that bring together emergency and disaster risk management (World Health Organization [WHO], 2019) and climate-resilient health systems (WHO, 2023), in practice the three domains are frequently governed by different agencies, funded through different mechanisms, and supported by incompatible data systems.

This narrative review addresses that fragmentation. Its objectives are to (a) summarize the principal pathways through which climate-driven hazards generate health emergencies; (b) appraise the contribution of environmental surveillance, including newer tools such as wastewater monitoring and Earth observation; (c) review the methods and lessons of disaster epidemiology; (d) examine the attributes of resilient health systems; and (e) propose an integrated framework, with practical implementation considerations, that links these domains to strengthen health security. By combining evidence that is usually presented separately, the review aims to support policy-makers, public health practitioners, and researchers designing coherent systems for anticipating and responding to climate-driven health emergencies.

2. REVIEW APPROACH

A narrative review design was selected because the topic spans several disciplines, uses heterogeneous study designs, and is evolving rapidly, which limits the suitability of quantitative pooling. The review draws on peer-reviewed articles, major institutional reports, and authoritative guidance published between 2017 and 2024, identified through structured searches of bibliographic databases such as PubMed, Scopus, and Web of Science, supplemented by documents from the WHO, the IPCC, and the United Nations Office for Disaster Risk Reduction [UNDRR]. Search concepts combined climate change, extreme weather, health emergencies, environmental and wastewater surveillance, early warning systems, disaster epidemiology, and health-system resilience.

Sources were retained when they offered original evidence, high-quality syntheses, conceptual frameworks, or operational guidance directly relevant to the integration of the three domains. Priority was given to global and multi-country assessments,

evidence from low- and middle-income settings, and studies of major recent events. Findings were organized thematically and then synthesized into two tables and two conceptual figures. As in all narrative reviews, selection involves judgment and cannot be guaranteed to be exhaustive or free of selection bias; this limitation is discussed further in Section 9.

3. CLIMATE-DRIVEN HEALTH EMERGENCIES: HAZARDS AND PATHWAYS

Climate-driven health emergencies are best understood as the outcome of interacting hazards, exposures, and vulnerabilities rather than as weather events alone. The IPCC risk framing treats risk as arising from hazard, exposure, and vulnerability, with adaptive capacity shaping the final outcome (Change, 2022). This framing is useful for health security because it directs attention to determinants that health systems can influence, such as population susceptibility, access to care, and facility robustness, alongside hazards that they cannot control. It also explains why identical hazards produce very different health consequences in different places. The following subsections summarize the principal hazards, with emphasis on the pathways that create demands for surveillance, epidemiological assessment, and system response.

3.1 Heat and temperature extremes

Heat is the most direct and best-quantified climate hazard for human health. Multi-country modelling projected substantial increases in temperature-related excess mortality under high-emission scenarios, with the largest increases in warm, lower-income regions (Gasparrini et al., 2017). A global analysis of non-optimal ambient temperature estimated that these exposures were associated with millions of excess deaths annually between 2000 and 2019, the majority attributable to cold but with a rising heat-related share in many regions (Zhao et al., 2021). Attribution research has shown that a considerable fraction of recent heat-related deaths can be linked to human-induced climate change (Vicedo-Cabrera et al., 2021). The summer of 2022 in Europe illustrated that even high-income, well-resourced health systems can experience tens of thousands of heat-related deaths in a single season (Ballester et al., 2023). Heat acts through heat stroke, cardiovascular and renal complications, adverse pregnancy outcomes, and exacerbation of chronic disease, and it also degrades the functioning of health facilities through power failures, cooling demand, and workforce strain (Ebi et al., 2021).

3.2 Floods, storms, and other extreme events

Floods and tropical cyclones affect health through drowning and injury, but also through contamination of water supplies, damage to sanitation and health infrastructure, displacement, and interruption of chronic disease care. A review of flood-related health risks highlighted the role of waterborne and vector-borne infection, wound infection, and long-term mental health consequences, and noted that effects often persist well after waters recede (Paterson et al., 2018). Extreme weather events place simultaneous demands on surveillance, clinical services, and logistics, and their consequences depend heavily on pre-existing vulnerability and on the integrity of health-system functions during and after impact (Ebi et al., 2021).

3.3 Wildfire smoke and air pollution

Wildfires are lengthening in season and expanding in extent in many regions, exposing large populations to fine particulate matter and other pollutants. Reviews have linked wildfire smoke to respiratory and cardiovascular morbidity, adverse mental health outcomes, and mortality (Xu et al., 2020). A global time-series analysis across 749 locations estimated meaningful mortality burdens attributable to wildfire-related fine particulate pollution (Chen et al., 2021). Smoke can travel far beyond fire perimeters, so population exposure frequently falls on communities with little direct experience of fire and limited preparedness, a pattern that strengthens the case for air-quality surveillance linked to health advisories.

3.4 Climate-sensitive infectious diseases

Climate influences infectious disease through effects on pathogen survival, vector biology, host behavior, and human exposure. A systematic mapping concluded that more than half of known human pathogenic diseases have been aggravated at least once by climatic hazards (Mora et al., 2022). Modelling of mosquito-borne diseases indicates expansion and redistribution of transmission suitability for Aedes-borne viruses (Ryan et al., 2019), and projections of dengue and malaria suggest rising populations at risk under warmer, more populous scenarios (Colón-González et al., 2021). Estimates of the current global distribution of dengue underline the scale of the population already living in suitable areas (Messina et al., 2019). In Europe, climate change has been linked to northward and altitudinal shifts in vector-borne and water-related infections (Semenza & Paz, 2021).

Water- and foodborne threats are also climate sensitive. Non-cholera vibrios are considered a microbial barometer of climate change because their abundance and infections respond to sea-surface temperature and salinity (Baker-Austin et al., 2017). Environmental suitability models for Vibrio infections in the Baltic region have been used to design early warning systems (Semenza et al., 2017). More broadly, climate change may alter cross-species viral transmission as species ranges shift and form new contacts (Carlson et al., 2022), and land-use change influences zoonotic host communities (Gibb et al., 2020). These findings imply that environmental and ecological observation must be part of any forward-looking infectious disease surveillance system.

3.5 Mental health and compounding vulnerabilities

Climate hazards also generate substantial psychological burden, including anxiety, depression, post-traumatic stress, and substance use, particularly after disasters, displacement, and loss of livelihoods (Cianconi et al., 2020). Hayes et al. (2018) described risks and priority actions for mental health, emphasizing the need to integrate mental health into disaster preparedness and to attend to both acute and chronic stressors. These burdens are not evenly distributed. People who are older, live in poverty, have chronic disease, work outdoors, or lack secure housing and infrastructure are systematically more exposed and less able to adapt. Table 1 summarizes the principal hazard–health pathways and the surveillance and response functions that correspond to each.

3.6 Compound and cascading events

Climate hazards rarely occur in isolation. Heatwaves may coincide with drought, power shortages, and wildfire smoke; floods may follow prolonged dry periods and strike communities already weakened by food insecurity; and storms may disable hospitals precisely when injuries and chronic-disease crises peak. Amaratunga et al. (2023) highlighted that such systemic and cascading risks are poorly captured by planning that treats hazards one at a time. For health security this has three implications. Surveillance must be capable of detecting multiple simultaneous signals; epidemiological assessment must be able to separate overlapping exposures, such as heat and particulate pollution; and health-system plans must anticipate the simultaneous loss of enabling services such as energy, water, and transport (Ebi et al., 2021). Compound events also complicate communication, because the public must interpret several warnings at once, and they raise the risk that response resources are exhausted before recovery from the previous event is complete.

Table 1. Climate hazards, health pathways, and corresponding surveillance and response functions

Hazard	Principal health pathways	Key surveillance data streams	Priority response functions
Extreme heat	Heat stroke; cardiovascular and renal events; adverse pregnancy outcomes; facility and workforce strain (Ebi et al., 2021; Gasparrini et al., 2017)	Temperature forecasts; mortality and emergency-visit data; vulnerable-population registers	Tiered heat–health alerts; outreach to at-risk groups; cooling access; hospital surge planning
Floods and storms	Drowning and injury; water contamination; infection; displacement; care interruption (Paterson et al., 2018; Kishore et al., 2018)	Rainfall and river forecasts; water quality and wastewater signals; facility status reports	Rapid assessment; safe water and sanitation; chronic care continuity; mortality tracking
Wildfire smoke	Respiratory and cardiovascular disease; mental health effects; mortality (Xu et al., 2020; Chen et al., 2021)	Satellite fire and smoke data; fine-particle monitoring; respiratory syndromic data	Air-quality advisories; clean-air shelters; protection of workers; medication access
Vector-borne disease	Altered transmission range and season for dengue and other	Climate suitability models; vector surveys; case reporting	Seasonal vector control; clinical preparedness; community engagement

	arboviruses (Ryan et al., 2019; Messina et al., 2019)		
Water- and foodborne disease	Vibrio and enteric infections linked to warming waters and flooding (Baker-Austin et al., 2017; Semenza et al., 2017)	Sea-surface temperature; wastewater and environmental water testing; laboratory reports	Risk maps; water safety measures; clinician and public advisories
Cross-cutting mental health	Anxiety, depression, post-traumatic stress after disasters and loss (Cianconi et al., 2020; Hayes et al., 2018)	Service-use data; community surveys; post-event screening	Psychosocial support; integration in primary care; long-term follow-up

4. ENVIRONMENTAL SURVEILLANCE FOR EARLY DETECTION AND ANTICIPATION

4.1 Climate-informed early warning

Early warning systems translate environmental observations and forecasts into actionable information for health decision-makers. Climate information can inform public health action across timescales, from seasonal outlooks that guide preparedness planning to short-range forecasts that trigger operational responses (Thomson & Mason, 2018). Health early warning is most effective when thresholds are linked to defined actions, responsible agencies, and communication channels, rather than when forecasts are simply published. The Vibrio early warning work cited above illustrates a practical model in which satellite-derived sea-surface temperature and salinity data were combined with epidemiological information to generate risk maps for health authorities (Semenza et al., 2017). Similar logic underlies heat–health warning systems and dengue forecasting, which have been shown to benefit from the explicit incorporation of delayed and nonlinear climate effects and of hydrometeorological and urbanization factors (Lowe et al., 2021).

4.2 Earth observation and remote sensing

Satellite Earth observation offers continuous, spatially comprehensive measurement of temperature, precipitation, vegetation, surface water, and air quality, which is especially valuable where ground monitoring is sparse. A scoping review of the use of satellite data in modelling malaria, dengue, and West Nile virus found a growing body of work using remotely sensed environmental variables as predictors, while noting challenges of validation, resolution, and translation into operational tools (Parselia et al., 2019). For health security, the practical value of remote sensing lies in coupling it with local health data, so that environmental anomalies can be interpreted in terms of likely health demand. Without such coupling, satellite products remain scientific outputs rather than decision-support tools.

4.3 Wastewater and pathogen surveillance

The COVID-19 pandemic accelerated the development of wastewater surveillance. Early studies showed that SARS-CoV-2 RNA concentrations in wastewater tracked community infection dynamics and could provide signals ahead of clinical case reporting (Peccia et al., 2020). Since then, wastewater monitoring has been proposed as an anchor for broader global disease surveillance, because it can capture population-level information independent of care-seeking behavior and can be extended to multiple pathogens and antimicrobial resistance markers (Keshaviah et al., 2023). For climate-driven emergencies, the relevance is considerable. Flooding, displacement, and infrastructure failure raise the risk of enteric and waterborne outbreaks, and wastewater or environmental water testing can provide rapid, low-cost community-level signals when clinic-based reporting is disrupted.

However, the global distribution of this capacity is highly unequal. A review of global monitoring efforts found that coverage was concentrated in high-income countries and that equity and data-sharing gaps were substantial, with limited representation of populations lacking sewered sanitation (Naughton et al., 2023). Adaptation to settings dominated by on-site sanitation, such as sampling from drains, septic systems, or surface waters, is therefore a priority for equitable climate-health surveillance. Interpretation also requires attention to rainfall dilution, flow normalization, and sampling design, all of which are directly influenced by the weather conditions that surveillance is meant to anticipate.

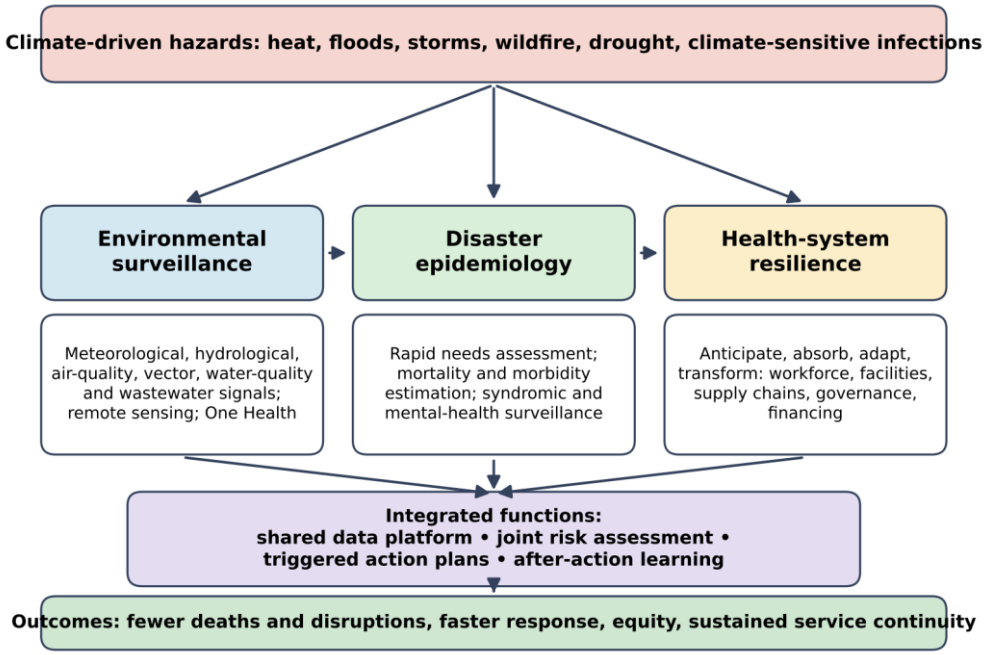
4.4 One Health and ecosystem observation

One Health recognizes the interdependence of human, animal, plant, and environmental health. The concept has matured over more than a decade but its implementation has often remained limited by sectoral boundaries (Destoumieux-Garzón et al., 2018). An international expert panel proposed an updated definition emphasizing integrated, unifying approaches to sustainably balance and optimize the health of people, animals, and ecosystems (Adisasmito et al., 2022). For climate-driven threats, One Health surveillance provides a logical home for integrating vector surveillance, animal disease monitoring, ecological observation, and human syndromic data. Evidence that environmental change alters zoonotic host communities and cross-species transmission risk (Carlson et al., 2022; Gibb et al., 2020) strengthens the argument that these data streams should feed a common risk assessment process rather than remain in separate ministries.

4.5 Limitations and enabling conditions

Environmental surveillance has well-recognized limitations. Data are frequently collected by non-health agencies in formats and at spatial scales that do not match health administrative units, thresholds are rarely validated locally, and signals can generate false alarms that erode trust. Sustained value depends on data-sharing agreements, interoperable standards, technical capacity at subnational levels, and clear protocols that define who acts on which signal. Local meteorological services, environmental agencies, water utilities, and veterinary services must therefore be treated as partners in health security, with formal roles in national preparedness plans. Figure 1 presents an integrated framework that situates environmental surveillance alongside disaster epidemiology and health-system resilience.

Figure 1. Integrated framework linking environmental surveillance, disaster epidemiology, and health-system resilience



4.6 Design principles for climate-sensitive surveillance

Drawing on the evidence above, five design principles can guide the development of environmental surveillance for health security. First, signals should be selected for decision relevance, which means that each indicator is linked in advance to a threshold and a responsible actor, rather than collected simply because it is available. Second, systems should be multi-scale, combining global and regional forecasts with local ground observations, because climate services are often most uncertain at the scale at which health services operate (Thomson & Mason, 2018). Third, they should be multi-hazard and multi-pathogen where possible, which is more efficient than parallel single-purpose systems and supports detection of compound events (Amaratunga et al., 2023). Fourth, they should be equity-aware, ensuring coverage of populations that are least visible to conventional systems (Naughton et al., 2023). Fifth, they should be learning systems, with routine evaluation of sensitivity,

timeliness, false-alarm rates, and the use of information in decisions. Applying these principles helps prevent surveillance from becoming a data-collection exercise detached from public health action.

5. DISASTER EPIDEMIOLOGY: MEASURING AND RESPONDING TO HEALTH IMPACTS

5.1 Mortality and morbidity estimation

Disaster epidemiology provides the evidence that links hazards to population health outcomes and guides resource allocation. One of its most important and contested tasks is the accurate measurement of mortality. Official death tolls often capture only direct deaths recorded at the time of impact, whereas indirect deaths caused by disrupted care, loss of power, contaminated water, or delayed treatment may account for a much larger toll. The experience of Hurricane Maria in Puerto Rico is instructive. A household survey estimated a substantially higher number of excess deaths than the official figure, with interruption of medical services identified as a major contributor (Kishore et al., 2018). An independent time-series analysis of vital statistics likewise found persistent excess mortality, with elevated risk among low-development municipalities and older and male residents over many months (Santos-Burgoa et al., 2018).

These studies highlight methodological choices that matter for health security. Excess-mortality methods compare observed deaths against expected baselines derived from prior years and therefore require timely, high-quality vital registration. Survey-based methods can work where registration is weak but depend on sampling design and recall. Both approaches can be strengthened through predefined protocols, rapid access to mortality records, and standard criteria for attributing deaths to a disaster, so that a defensible estimate becomes available while response decisions are still being made. Heat-related mortality assessments illustrate the same principle: recent analyses in Europe demonstrated that systematic, near-real-time monitoring of deaths can reveal the scale of a heat emergency that may otherwise remain unseen (Ballester et al., 2023).

5.2 Rapid assessment and syndromic surveillance

In the acute phase of a disaster, traditional surveillance systems may be disrupted just as information needs peak. Rapid needs assessments, sentinel and syndromic surveillance of conditions such as injuries, diarrhea, acute respiratory infection, fever, and heat illness, and event-based surveillance of rumors and media reports can provide timely information to guide response. The WHO framework for health emergency and disaster risk management stresses that information management, community capacities, and multisectoral coordination are core to the whole-of-disaster cycle, including prevention, preparedness, response, and recovery (WHO, 2019). Floods illustrate the typical needs: monitoring of waterborne and vector-borne diseases, injuries, and exacerbations of chronic disease, together with rapid assessment of the functionality of health facilities and water and sanitation services (Paterson et al., 2018).

5.3 Mental health, long-term effects, and equity

The health consequences of disasters extend beyond the acute phase. Mental health disorders, chronic disease deterioration, and disrupted childhood development can persist for years, yet these outcomes are rarely tracked systematically. Reviews emphasize that psychological effects are common after extreme events and that sustained, community-based psychosocial support and routine mental health monitoring should be part of recovery planning (Cianconi et al., 2020; Hayes et al., 2018). Equity is central. The Puerto Rico evidence showed that risk of death was unequally distributed across municipalities according to social and developmental conditions (Santos-Burgoa et al., 2018), and global assessments of climate risk consistently identify differential vulnerability based on poverty, age, gender, disability, and geography (Change, 2022). Disaster epidemiology therefore needs disaggregated data, capable of revealing who is most affected, rather than aggregate totals that mask inequality.

5.4 Linking epidemiology back to environmental information

A critical function of disaster epidemiology in an integrated system is to calibrate the environmental signals described in Section 4. Retrospective analysis of how temperature, rainfall, smoke concentrations, or sea-surface conditions related to health outcomes allows the derivation of locally relevant thresholds and exposure–response functions. Attribution analyses, such as those quantifying heat deaths attributable to climate change (Vicedo-Cabrera et al., 2021) or mortality from wildfire-related particulate pollution (Chen et al., 2021), show how epidemiological methods can quantify the contribution of climate hazards to the burden of disease. When such estimates are generated routinely and shared with environmental agencies and health planners, they close the loop between hazard monitoring and response, and help justify investment in preparedness.

5.5 Field investigation, ethics, and communication

Disaster epidemiology is also a practical field discipline. Rapid-response and field epidemiology teams can verify signals, investigate clusters, and advise on control measures, but their effectiveness depends on pre-established deployment mechanisms, supplies, and security arrangements (WHO, 2019). Ethical considerations are prominent. Data collection from displaced or bereaved populations must avoid additional harm, protect confidentiality, and be proportionate to the information needed. Findings should be communicated transparently, including uncertainty, because disputes over mortality figures, as occurred after Hurricane Maria, can erode public trust and delay learning (Kishore et al., 2018; Santos-Burgoa et al., 2018). Finally, results must be returned to affected communities and to the services that serve them, so that epidemiological work contributes to recovery rather than serving only research or reporting purposes.

6. HEALTH-SYSTEM RESILIENCE TO CLIMATE-DRIVEN EMERGENCIES

6.1 Concepts and capacities

Resilience is widely used but variably defined. Scoping reviews have found that the concept is applied with differing emphases, ranging from the ability to absorb shocks to broader capacities for adaptation and transformation, and that clearer definitions and operational measures are needed (Fridell et al., 2020; Turenne et al., 2019). Kruk et al. (2017) proposed that resilient health systems are aware, diverse, self-regulating, integrated, and adaptive, and suggested constructing a resilience index to track these characteristics. Blanchet et al. (2017) emphasized governance and the capacity to manage resilience, highlighting the roles of leadership, stakeholder relations, and learning. Analysis of 28 countries during COVID-19 found that resilience in practice involved governance and coordination, health workforce capacity, service delivery adaptation, information systems, and community engagement, with considerable variation in how these were mobilized (Haldane et al., 2021).

6.2 Climate-resilient and low-carbon health systems

The WHO operational framework for climate-resilient and low-carbon health systems identifies components that include leadership and governance, health workforce, vulnerability and adaptation assessment, integrated risk monitoring and early warning, health and climate research, climate-resilient infrastructure and technologies, management of environmental determinants, climate-informed health programmes, emergency preparedness and management, and climate and health financing (WHO, 2023). Companion guidance for health care facilities emphasizes that hospitals and clinics must be safe, functional, and able to continue operation during and after extreme events, with attention to energy, water, sanitation, and thermal safety (WHO, 2020). These documents make clear that integrated risk monitoring and emergency preparedness are two of the components of a resilient system, which highlights the logical connection between surveillance, epidemiology, and system-level planning.

6.3 Facilities, workforce, and supply chains

Health facilities are both critical infrastructure and sources of vulnerability. Heat stress, flooding, and power or water outages can compromise cold chains, diagnostics, surgical capacity, and patient safety. Workforce resilience encompasses surge capacity, protection of health workers from heat and psychological stress, and continuity of care when staff are themselves affected by disasters. Experiences from COVID-19 and recent disasters show that supply-chain visibility and flexible procurement can determine whether essential services continue (Haldane et al., 2021). Service continuity for chronic disease management is particularly important, because interrupted medical care contributed substantially to indirect deaths after Hurricane Maria (Kishore et al., 2018).

6.4 Governance, financing, and adaptation progress

Despite growing recognition of climate risks, indicators suggest that health adaptation and financing have lagged behind the scale of threat. The Lancet Countdown reported that although a growing number of countries had undertaken vulnerability and adaptation assessments or developed health national adaptation plans, implementation and funding remained limited, and many health systems still lacked dedicated resources for climate response (Romanello et al., 2022, 2023). Analysis of International Health Regulations reporting similarly points to variation in preparedness capacities across countries (Kandel et al., 2020). Strengthening resilience requires sustained domestic and international investment, clear mandates for climate and health units within ministries of health, and regular assessment of capacities using measurable indicators. Table 2 sets out the components of an integrated system and example indicators that can support such assessment.

Table 2. Components of an integrated climate health security system and example indicators

Component	Core activities	Example indicators	Lead actors
Hazard detection and early warning	Integrate meteorological, ecological, wastewater, and vector data; issue tiered alerts (Thomson & Mason, 2018; Keshaviah et al., 2023)	Lead time of alerts; proportion of districts covered; alert-to-action interval	Meteorological and environmental agencies; public health institutes
Risk interpretation and disaster epidemiology	Derive local thresholds; rapid assessment; excess-mortality and morbidity estimation (Kishore et al., 2018)	Time to first mortality estimate; disaggregated reporting; validated thresholds	Epidemiology units; universities; statistical offices
Response and service continuity	Activate protocols; protect vulnerable groups; maintain essential services and facilities (WHO, 2020)	Share of facilities with continuity plans; supply stock-outs; surge staffing achieved	Ministries of health; hospitals; emergency management
Learning and adaptation	After-action review; update plans, thresholds, and investments (Haldane et al., 2021)	Reviews completed; recommendations implemented; resilience index score (Kruk et al., 2017)	Coordinating unit; external reviewers; communities
Enabling conditions	Governance, workforce, financing, community engagement, equity (WHO, 2023; Blanchet et al., 2017)	Dedicated budget; trained staff per district; equity-stratified data	Government; funders; civil society

6.5 Lessons from COVID-19 for climate-health resilience

The COVID-19 pandemic provides recent, large-scale evidence on what resilience requires, and many of its lessons transfer to climate-driven emergencies. Across 28 countries, effective responses combined strong governance and coordination with adaptable service delivery, transparent information, and trust in health authorities, whereas fragmented decision-making and weak communication undermined performance (Haldane et al., 2021). Analyses of reported capacities had already pointed to wide variation in readiness (Kandel et al., 2020), and a stated capacity does not by itself guarantee functioning in practice. For climate-driven emergencies, the implication is that resilience should be tested through simulations, exercises, and real events, with attention to how systems behave under sustained and recurrent stress rather than only single shocks. The pandemic also demonstrated the value of wastewater surveillance as a complementary data source when clinical testing was limited (Peccia et al., 2020), a function that can be repurposed for flood and displacement settings. Climate change makes recurrent stress the norm, which strengthens the argument for treating resilience as a continuous process of learning and adaptation (Blanchet et al., 2017; Turenne et al., 2019).

7. TOWARD AN INTEGRATED FRAMEWORK FOR HEALTH SECURITY

7.1 Core functions

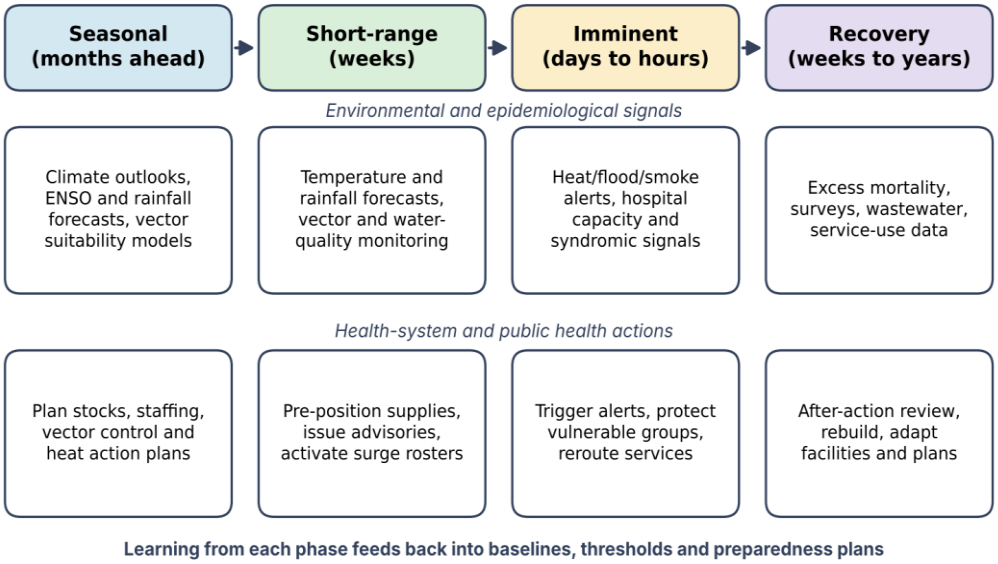
Integration does not mean merging institutions; it means connecting functions through shared information, joint risk assessment, and coordinated action. We propose four linked functions. The first is hazard detection and early warning, in which environmental, ecological, and pathogen data are monitored continuously and translated into tiered alerts. The second is risk interpretation, in which epidemiological analysis and exposure–response evidence convert environmental signals into estimates of expected health impact for defined populations and facilities. The third is response and service continuity, in which pre-agreed protocols mobilize workforce, supplies, communication, and protection for high-risk groups. The fourth is learning and adaptation, in which after-action reviews, mortality and morbidity assessments, and monitoring of equity outcomes inform

revisions to thresholds, plans, and investments. These functions rest on enabling conditions of governance, workforce, finance, and community engagement (Table 2).

7.2 Time horizons

Different decisions are needed at different timescales, and an integrated system should explicitly link signals and actions across them (Figure 2). Seasonal outlooks and vector suitability models can guide planning for vector control, staffing, and stockpiles months in advance (Thomson & Mason, 2018; Colón-González et al., 2021). Short-range forecasts and monitoring support pre-positioning of supplies and issuing advisories. Imminent hazards require rapid alerts and protection of vulnerable groups. Recovery requires systematic measurement of mortality, morbidity, and mental health outcomes and rebuilding according to updated risk. A strength of this structure is that every phase generates information that improves the next, but this only occurs when data flow back to the agencies that set thresholds and plans.

Figure 2. Time horizons linking environmental and epidemiological signals to health-system actions



7.3 Shared data and interoperability

Shared data architecture is the technical backbone of integration. At minimum it should combine environmental observations and forecasts, health facility and syndromic data, mortality records, wastewater and vector data, and information on facility status and resources, all geo-referenced to units used for decision-making. Experience from wastewater programs shows that standardized methods, transparent data-sharing, and links to public health action are prerequisites for utility (Keshaviah et al., 2023; Naughton et al., 2023). Satellite-derived products are most useful when presented in forms familiar to health users and tested against local health data (Parselia et al., 2019). Privacy-protective approaches that allow aggregate sharing across sectors are essential, as are common vocabularies and metadata that enable comparison between regions and over time.

7.4 Decision rules and action triggers

Integration is only valuable if it changes decisions. This requires translating continuous information into discrete triggers linked to responsibilities. Heat–health action plans, for example, may define alert levels based on forecast temperature and expected mortality, each associated with communication to the public, outreach to isolated older adults, cooling center activation, and adjustment of hospital capacity. Similar trigger-based protocols can be developed for floods, smoke events, and outbreak risk. The evidence from the Vibrio early warning system and dengue forecasting models demonstrates that predictive tools can be built, but the literature indicates that the translation into routine operational decisions remains the weakest link (Semenza et al., 2017; Lowe et al., 2021). Testing triggers through simulation exercises, and revising those using after-action reviews, can improve both credibility and performance.

7.5 An illustrative scenario

A stylized example shows how the functions interact. Seasonal climate outlooks indicate a hotter-than-normal season with above-average rainfall in a coastal region. At the seasonal horizon, the health ministry and the meteorological service review vector suitability and heat risk, update heat action plans, and adjust stocks of oral rehydration solution, vector-control supplies, and cooling equipment for facilities. As the season advances, forecast heat and heavy rainfall trigger advisories, and sea-surface warming prompts monitoring for Vibrio infections in line with the early-warning approach described above (Semenza et al., 2017). When a flood occurs, rapid assessment teams verify facility functionality and water safety, wastewater or water-quality testing identifies potential enteric hazards where clinical reporting is disrupted (Keshaviah et al., 2023), and syndromic data guide targeted response. In the recovery phase, excess-mortality estimation and mental health follow-up quantify the full burden, including indirect deaths (Kishore et al., 2018), and an after-action review updates thresholds and plans. No single component in this scenario is novel; the added value arises from agreeing roles, data flows, and triggers beforehand.

8. IMPLEMENTATION CONSIDERATIONS

8.1 Governance and institutional arrangements

Effective integration depends on clear mandates and standing coordination mechanisms among ministries of health, environment, meteorology, water, agriculture, veterinary services, and disaster management. A One Health coordination platform or national climate and health unit can fulfil this role, provided it has a budget, authority, and links to emergency operations centers (Destoumieux-Garzón et al., 2018; WHO, 2023). Subnational authorities frequently carry the practical burden of response and need data, tools, and training adapted to their level. Formal agreements for data-sharing and joint exercises can reduce friction during crises.

8.2 Workforce and capacity

Integrated systems require professionals who can work across disciplines, including climate-health analysts, environmental health officers, field epidemiologists, data scientists, and clinical managers. Training programs should combine environmental data interpretation with outbreak and disaster epidemiology and should include practice in risk communication. Because capacities vary widely across countries (Kandel et al., 2020), South–South collaboration, regional centers of excellence, and sustained mentoring may be more effective than short-term external support.

8.3 Equity and community engagement

Equity must be built into design rather than added afterwards. Surveillance coverage should be assessed for gaps affecting rural, informal, displaced, and marginalized communities, as shown by the limited coverage of wastewater programs in settings lacking sewerage (Naughton et al., 2023). Alerts and advisories should be accessible in relevant languages and channels and should address practical barriers to protective action, such as lack of cooling, safe water, or transport. Community participation improves the relevance of surveillance and the legitimacy of response, and it supports mental health recovery after disasters (Hayes et al., 2018). Disaggregated reporting by age, sex, income, disability, and location allows monitoring of whether integrated systems reduce or reinforce inequality (Change, 2022).

8.4 Financing and sustainability

Many promising surveillance and early-warning initiatives rely on project funding and fail when external support ends. Sustainable financing requires inclusion of climate-health surveillance and resilience in national health budgets, national adaptation plans, and disaster risk financing, together with access to international climate finance (WHO, 2023; Romanello et al., 2023). Because avoided mortality and service disruption are difficult to quantify, evaluation methods that document outcomes and costs are needed to build the investment case. The UNDRR emphasis on systemic risk suggests that integrated investments should be justified in terms of avoided cascading losses across sectors, and not only in terms of health-sector savings (Amaratunga et al., 2023).

8.5 Emerging tools and their governance

New tools, including machine-learning forecasting, high-resolution Earth observation, mobile data, and genomic and environmental DNA methods, can extend detection and prediction capabilities. Their value depends on data quality, local validation, transparency, and ethical safeguards. Statistical and process-based models used for dengue and other diseases have

shown that incorporating climate lags, urban context, and population dynamics can improve skill (Lowe et al., 2021), while projections remain sensitive to scenario assumptions (Colón-González et al., 2021). Decision-makers should therefore receive uncertainty information alongside forecasts, and tools should be evaluated prospectively against operational outcomes rather than retrospective accuracy alone.

8.6 Monitoring and evaluation

Monitoring and evaluation should be designed at the outset. A minimal set of indicators can track the performance of each function: the timeliness and geographic coverage of environmental signals, the interval between alert and action, the timeliness and completeness of mortality and morbidity assessment, the continuity of essential services during events, and equity of outcomes across population groups. Composite measures such as the resilience index proposed by Kruk et al. (2017) can complement these functional indicators, although validation against health outcomes remains limited (Fridell et al., 2020). Reporting against the indicators in Table 2 annually, and after each significant event, creates accountability and allows comparison across jurisdictions. Independent review, whether by academic partners or regional bodies, can reduce the risk that systems assess themselves too favorably. Over time, a cumulative record of exposures, responses, and outcomes can also provide the evidence needed to refine economic and policy arguments for sustained investment (Romanello et al., 2022).

9. RESEARCH GAPS, LIMITATIONS, AND PRIORITIES

Several gaps limit progress. First, there is little rigorous evaluation of whether integrated early warning and response systems reduce morbidity and mortality; most evidence concerns forecast skill or process rather than health outcomes. Second, indicators of health-system resilience remain contested and rarely validated against outcomes (Fridell et al., 2020; Turenne et al., 2019). Third, data from low- and middle-income countries, which face the highest climate vulnerability, are sparse, as illustrated by the uneven geographic distribution of wastewater surveillance (Naughton et al., 2023) and the variability in reported health-security capacities (Kandel et al., 2020). Fourth, compound and cascading events are poorly represented in models and plans (Amaratunga et al., 2023). Fifth, mental health, chronic disease, and long-term outcomes are under-measured relative to acute injury and infection (Cianconi et al., 2020).

This review has its own limitations. As a narrative synthesis it is not exhaustive, and the selection of studies reflects the authors' judgment and the dominance of English-language, high-profile publications. Rapidly evolving events and publication lags mean some recent evidence may be missing. The proposed framework is conceptual, derived from the literature rather than empirically tested, and it will need adaptation to national governance structures and resource constraints. Priority research includes prospective evaluation of integrated systems, development and validation of resilience indicators, studies of cost-effectiveness, implementation research in resource-limited settings, and methods for analyzing compound hazards.

10. CONCLUSION

Climate change is transforming the landscape of health emergencies, expanding the range of hazards that health security systems must anticipate and manage. The literature reviewed here shows that the necessary components exist in some form: environmental observation and forecasting, wastewater and ecological surveillance, rigorous disaster epidemiology, and growing guidance on climate-resilient health systems. What is lacking is their integration into a coherent, funded, and equitable system in which signals reliably lead to timely, protective action. Strengthening health security therefore requires linking hazard detection, epidemiological interpretation, service continuity, and learning through shared data, defined triggers, and clear governance.

Priorities for action include establishing cross-sector coordination mechanisms with mandates and budgets; building interoperable data platforms that connect environmental and health information at subnational scale; investing in workforce and facility resilience; ensuring that equity is measured and addressed; and evaluating integrated systems against health outcomes. As the Lancet Countdown has repeatedly emphasized, the health case for rapid mitigation and ambitious adaptation is strong (Romanello et al., 2023). Integrating environmental surveillance, disaster epidemiology, and health-system resilience offers a practical route for protecting populations from the climate-driven emergencies that can no longer be avoided and must therefore be better anticipated.

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تعزيز الأمن الصحي في مواجهة الطوارئ الصحية الناجمة عن المناخ: دمج المراقبة البيئية، وعلم أوبئة الكوارث، ومرونة النظم الصحية

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الملخص

يزيد تغير المناخ من تواتر الطوارئ الصحية وشدتها وتراكبها، بما في ذلك موجات الحرارة، والفيضانات، وحرائق الغابات، والعواصف، وتفشي الأمراض المعدية الحساسة للمناخ. ومع ذلك، لا تزال المراقبة البيئية، وعلم أوبئة الكوارث، والاستعداد الصحي للنظم الصحية تُطوَّر عادةً في صوامع مؤسسية منفصلة. تستعرض هذه المراجعة السردية الأدبيات المحكَّمة والمؤسسية المنشورة بين عامي 2017 و2024 لبحث كيفية دمج هذه المجالات الثلاثة لتعزيز الأمن الصحي. ونلخص المسارات الرئيسية بين المخاطر والصحة، ونقيّم المراقبة البيئية ومراقبة مياه الصرف الصحي، والاستشعار عن بُعد، ونهج الصحة الواحدة(One Health) ، ونراجع أساليب علم أوبئة الكوارث لقياس الوفيات والمراضة والعبء على الصحة النفسية. ثم نربط هذه الوظائف بقدرات مرونة النظم الصحية. ويُقترح إطاراً تكاملياً يربط بين كشف المخاطر، وتفسير المخاطر، والاستجابة، والتعلم. وتشمل الفجوات المستمرة تشتت البيانات، وضعف القدرات دون الوطنية، واللامساواة، ومحدودية التقييم. وتُؤخذ في الاعتبار الأدلة المستمدة من التقييمات العالمية والأحداث الكبرى الأخيرة. وتُحدَّد أولويات للسياسة والممارسة والبحث لدعم استعداد منصف ومستنير بالأدلة.

الكلمات المفتاحية: تغير المناخ؛ الأمن الصحي؛ المراقبة البيئية؛ علم أوبئة الكوارث؛ مرونة النظم الصحية