Review Article

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A Comprehensive Review of the Cascading Public Health Consequences of Hydrological Disasters: Epidemiological, Toxicological, Nutritional, and Psychosocial Impacts

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Abstract:

Hydrological disasters, primarily floods and tropical cyclones, represent the most frequent and devastating natural hazards globally. Driven by anthropogenic climate change, extreme precipitation events are increasing in both frequency and severity, creating complex public health emergencies that extend far beyond the acute impact phase. This comprehensive review synthesizes current epidemiological, clinical, toxicological, nutritional, and psychological evidence to elucidate the multi-dimensional health impacts of flooding. We examine global mortality trends and the mechanisms of acute physical trauma and healthcare utilization. Furthermore, we detail the subsequent surge in infectious diseases, emphasizing waterborne pathogens, zoonotic outbreaks (particularly leptospirosis), and vector-borne diseases. This updated review highlights the critical consequences of man-made toxicological exposures triggered by the inundation of industrial infrastructure and the underreported nutritional deficits caused by flood-induced food insecurity. We explore the enduring burden of psychological morbidity, demonstrating how displacement, secondary stressors, compounding disaster exposures, and pre-existing social vulnerabilities mediate long-term mental health trajectories. Finally, we evaluate the evolution and readiness of Multi-Hazard Early Warning Systems and digital infrastructure. Effective mitigation requires precision public health interventions, targeted social support, resilient digital warning systems, and extended community-based resilience strategies.

Keywords: anthropogenic climate change, epidemiological synthesis, health impacts, hydrological disasters, public health emergencies

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Introduction

Hydrological disasters, primarily floods and tropical storm-induced inundations, constitute the most frequent and costly category of natural hazards worldwide. Driven by anthropogenic climate change, rising atmospheric temperatures have intensified the global hydrological cycle, increasing the frequency, volume, and spatial unpredictability of extreme precipitation events[1]. Between 1990 and 2022, 4,713 major floods were recorded globally, resulting in 218,353 acute deaths[2]. Beyond immediate mortality, the systemic economic disruption is massive; in the United States alone, the annual economic cost of flooding is estimated between $179.8 billion and $496 billion[3]. Paralleling these environmental shifts, academic research investigating climate change and water-related diseases has surged rapidly, reaching a peak of 125 major publications in 2024 alone[4].

The public health toll of hydrological disasters is characterized by a distinct temporal evolution and marked global health inequities. Spatial exposure modeling indicates that over 780 million individuals living on less than $5.50 per day face high flood risk[5]. A nation's socioeconomic baseline serves as a primary determinant of survival. An ecological study of 168 countries, based on the International Disaster Database for 1990–2022, reported that the odds of a flood event causing more than 50 deaths are 14.34 times higher in low-income countries compared to high-income ones[2]. While official disaster metrics routinely measure acute drowning and physical trauma, the routine metrics often do not include delayed and cause-specific mortality, which includes late-onset infectious disease deaths, worsening of pre-existing chronic diseases, including diabetes, cardiovascular and chronic kidney diseases, and morbidities related to mental diseases[6].

The health consequences of flooding transition rapidly across distinct disaster phases. In the acute impact phase, health risks are dominated by mechanical trauma, drowning, and acute surgical emergencies[6]. As floodwaters recede, the destruction of water, sanitation, and hygiene infrastructure initiates a second wave of public health threats[7]. These include microbiological proliferation, zoonotic spillover (such as *Leptospira* dissemination)[7], vector-borne disease surges, toxicological exposures from inundated industrial facilities, agricultural destruction leading to household food insecurity, and long-term psychological morbidity[6].

Mitigating these multi-phase public health threats depends on modern adaptation systems and proactive public health infrastructure. The World Meteorological Organization (WMO) emphasizes that issuing an effective early warning just 24 hours prior to an event can reduce disaster-related damage by 30%[8]. Driven by major global initiatives such as Target G of the Sendai Framework (2015–2030) and the UN's Early Warnings for All (EW4All) initiative targeting universal coverage by 2027, disaster risk management has fundamentally shifted from traditional single-hazard models toward integrated Multi-Hazard Early Warning Systems (MHEWS)[9]. Crucially, disaster-related mortality is nearly six times lower in nations equipped with comprehensive MHEWS capabilities compared to those with limited infrastructure[10]. Nevertheless, critical adaptation gaps remain; for instance, only 43% of Small Island Developing States (SIDS) currently possess functional early warning coverage[10].

To address the need for an integrated framework, this review provides a systematic synthesis of the cascading public health impacts of hydrological disasters across five core themes. First, the epidemiological synthesis addresses the mortalities, waterborne pathogen dynamics, zoonotic diseases—specifically leptospirosis floodwater contact risk and vector-borne climatic lag phases. Second, trauma and acute exacerbations of chronic diseases assess acute physical injury patterns, alongside acute exacerbations of chronic conditions, including diabetes and respiratory diseases. Third, nutritional deficits and food insecurity analyze agricultural destruction and household food security crises. Fourth, psychosocial morbidity addresses

post-traumatic stress disorder (PTSD), displacement-driven mental health disparities, and compounding disaster trajectories. Finally, adaptation systems and early warning infrastructure evaluate global readiness, technological capabilities that reduce disaster mortality nearly sixfold, and targeted public health interventions such as pre-emptive vaccination campaigns achieving 82% population coverage. The summaries and examples of the five themes are shown in Table 1.

Epidemiological flood-related events

Global flood mortality trends and cause-specific delayed mortality

The distribution of flood-related health impacts reflects deep global inequities, falling disproportionately on low-income nations and impoverished communities. Global spatial estimates indicate that over 780 million people living on less than $5.50 per day face high flood risk; consequently, four out of every ten people exposed to flood risk globally live on low incomes. The socioeconomic status of a country is a dominant predictor of flood mortality. Statistical models reveal that the odds of a flood causing more than 50 deaths are 14.34 times higher (95% confidence interval [CI]: 7.46–30.04) in low-income countries compared to high-income countries[2]. Furthermore, while official metrics consistently capture acute fatalities (with global disaster deaths averaging 45,000 people annually[11]), long-term, cause-specific mortality is vastly underestimated. A study by Lynch et al. demonstrated that very severe floods in the United States, particularly those driven by tropical cyclones and extreme precipitation, lead to significant increases in mortality from cardiovascular diseases, infectious diseases, and injuries[12]. Heavy rain-related floods were associated with a 3.2% increase in infectious disease deaths and a 2.1% increase in cardiovascular deaths[12]. While these delayed mortality metrics are documented in high-income settings with robust death registries, the true magnitude of post-flood delayed mortality in low-income nations remains an unquantified public health emergency, where destroyed water, sanitation, and hygiene (WASH) infrastructure and disrupted chronic disease care are likely to exacerbate these figures far beyond the observed Western baselines.

Waterborne pathogen dynamics and post-flood gastrointestinal disease

The post-impact phase of a hydrological disaster (typically spanning 4 days to 4 weeks post-event) is heavily characterized by the rapid onset of waterborne gastrointestinal illness. As floodwaters recede, the inundation and catastrophic collapse of WASH infrastructure serve as the primary catalyst for disease transmission[13]. Floodwaters routinely breach municipal sewage lines, inundate pit latrines, and wash agricultural runoff into surface water reservoirs and private pond supplies. This infrastructure failure leads to the severe microbiological contamination of drinking water and food supplies with a wide spectrum of pathogenic organisms, including *Vibrio cholerae*, *Salmonella*, *Shigella*, toxigenic *Escherichia coli*, *Salmonella* enterica serovar Typhi, Hepatitis A and E viruses, and Norwalk virus[13]. The magnitude of post-flood waterborne outbreaks has been documented across diverse geographic and economic settings. Major municipal contamination events demonstrate the vulnerability of public water systems during extreme precipitation. For example, in the Walkerton outbreak in 2000, heavy rainfall and agricultural runoff led to municipal water supply contamination, resulting in 1,346 reported gastroenteritis cases[14]. After the German flood disaster in 2002, a post-disaster epidemiological surveillance revealed a 6.9% diarrheal incidence rate among flooded households, driven by private well contamination and compromised municipal distribution networks[15].

Overcrowding in emergency displacement shelters significantly exacerbates transmission kinetics, transforming localized water contamination into explosive person-to-person diarrheal outbreaks. A critical surveillance disparity exists between country settings. While high-income nations

capture localized outbreaks through automated water testing and electronic health registries, the true burden of post-flood cholera and dysentery in low- and middle-income nations remains substantially underestimated. In these resource-limited environments, baseline WASH precarity combines with flood-induced infrastructure loss to drive high case-fatality rates, underscoring the vital necessity of pre-emptive WASH restoration and rapid oral vaccine deployment.

Zoonotic diseases

Leptospirosis is arguably the most widespread zoonotic disease associated with flooding. A robust meta-analysis of 18 observational studies confirmed that contact with floodwater significantly increases the risk of human leptospirosis, yielding a pooled odds ratio (OR) of 2.19 (95% CI: 1.48–3.24)[16]. This meta-analysis highlights three critical predictors that significantly increase the risk of *leptospira*l infection following flood events. The most substantial risk factor is the presence of lacerated wounds, which increases the likelihood of infection more than fourfold (OR=4.35), as open skin provides a direct entry point for the bacteria in contaminated water. Demographic and environmental factors also play a major role, with male gender (OR=2.06) and exposure to livestock or animals (OR=1.95) both roughly doubling the risk of infection[16]. These findings suggest that post-flood public health strategies should prioritize wound care, animal-contact precautions, and targeted outreach to high-risk demographic groups in order to mitigate the spread of leptospirosis.

The surge in leptospirosis following floods is driven by the pathogen's remarkable environmental resilience. *Leptospira* bacteria are shed in the urine of infected mammals. Heavy flooding prevents this urine from evaporating or being absorbed safely into the soil, keeping the bacteria highly viable in standing water, agricultural runoff, and mud[16]. When humans wade through these contaminated environments, the spirochetes easily penetrate the body through lacerations or intact mucous membranes (such as the conjunctiva of the eyes and the nasopharynx)[13].

Following an incubation period of 5 to 14 days, the disease typically manifests as a flu-like illness characterized by fever, severe myalgias, chills, and headache. If left untreated, the infection can rapidly deteriorate into life-threatening conditions, including renal failure, jaundice (Weil's disease), severe pulmonary hemorrhage, and acute respiratory distress syndrome (ARDS)[13,17]. The scale of this threat remains substantial; for instance, the Philippines frequently reports thousands of leptospirosis cases following major typhoons and monsoon floods[18].

While exposure to livestock (such as cattle, goats, and sheep) and stray pets represents a significant risk, rodents remain the most pervasive reservoir for flood-related zoonotic outbreaks[16,18]. Floods inundate rodent burrows in both urban areas and agricultural fields, forcing massive rodent populations into closer proximity with humans and their food supplies. Notably, the peridomiciliary "sighting of rats" is frequently cited as an additional risk factor during post-flood recovery[16].

Alarmingly, these displaced rodents frequently carry multiple zoonotic pathogens simultaneously. Environmental surveillance studies in Southeast Asia have identified rodents co-infected with *Leptospira*, *Orthohantavirus*, *Rickettsia* (typhus), and *Bartonella*[18]. This multi-pathogen carriage creates a severe risk for complex co-infections in humans, which can easily be misclassified during post-disaster triage and complicate clinical management. Furthermore, floodwaters also mobilize other zoonotic pathogens, such as the protozoan parasites *Cryptosporidium* and *Giardia*, which can be transmitted to humans through contaminated water interacting with animal feces[18].

Beyond waterborne transmission, the chaotic displacement of human and animal populations during floods leads to a sharp increase in traumatic animal bites. Distressed domestic pets, stray animals, and displaced

wildlife frequently interact with flood survivors and emergency responders, resulting in defensive bites and scratches. These injuries bypass the need for contaminated water, acting as a direct vector for zoonotic pathogens. Delayed wound care and the lack of immediate prophylactic antibiotics frequently result in severe soft tissue infections driven by the biting animal's oral flora[13].

To effectively combat the spread of zoonotic diseases after a flood, public health interventions must be multi-pronged. Administering prophylactic antibiotics (such as oral doxycycline) to high-risk groups and emergency responders who have been heavily immersed in floodwaters can significantly reduce the incidence of clinical leptospirosis[13]. The long-term reduction of zoonotic diseases requires municipal-level interventions. Improving sanitation, garbage disposal, and sewage systems in communities reduces food sources for rodents, actively mitigating rat infestations and subsequent exposure to environments contaminated by their urine[16]. Medical personnel must aggressively treat animal bites and lacerations with thorough wound irrigation, appropriate empiric antibiotics, and evaluate the patient's need for a tetanus booster based on their vaccination history[13].

Vector-borne diseases (VBDs)

Flooding creates extensive stagnant water pools that serve as ideal breeding habitats for mosquito vectors. A systematic review of VBD outbreaks following natural disasters captured 30 distinct VBD outbreaks, demonstrating that malaria (reported in 16 studies) and dengue virus (reported in 11 studies) were the most frequently documented pathogens[11]. Furthermore, floods and hurricanes were the disaster types most predominantly associated with these vector-borne outbreaks globally[11].

The scale of these post-flood outbreaks can be massive. Following the catastrophic 2022 floods in Pakistan, malaria cases surged to at least 2.6 million, representing a five-fold increase from the 500,000 cases reported the year prior, alongside nearly 42,000 confirmed cases of dengue[19]. Similarly, local community studies, such as those following the 2013 floods in Western Uganda, demonstrated a 30% increase in the risk of an individual having a positive malaria diagnostic test in the post-flood period for villages bordering flooded rivers compared to those further away. After a 2008 flood in Brazil, 57,010 dengue cases and 67 associated deaths were reported among victims[11]. In 2024, following a succession of typhoons and flooding, the Philippines recorded nearly 341,000 dengue cases by mid-November, an 81% increase compared to the same period the previous year[20]. This trend is closely linked to climatic variables, as stagnant rainwater provides essential breeding sites for *Aedes aegypti* mosquitoes. Path analysis research from Indonesia shows that rainfall has a direct influence on disease occurrence, typically followed by a three-week lag before a spike in confirmed cases is observed[21].

Epidemiological data indicate that VBD outbreaks exhibit a distinct temporal lag phase following a disaster event. Disease incidence, particularly for dengue, may initially decrease in the first month as violent floodwaters wash away existing mosquito breeding sites, but it subsequently surges over the following two to three months as the water stagnates and vector populations explode[11]. Beyond malaria and dengue, floods have been linked to outbreaks of West Nile virus (WNV), Zika virus, Chikungunya, and Japanese encephalitis[11]. For instance, a resurgence of West Nile neuroinvasive disease cases was reported within three to four weeks following Hurricane Katrina, increasing from an average of 30 cases to 45 cases in Louisiana, and from 23 to 55 cases in Mississippi[11].

As floodwaters recede, the destruction of WASH infrastructure triggers a massive surge in communicable diseases. Topic modeling of the modern scientific literature reveals that malaria and dengue fever constitute over 40% (two-fifths) of all research on climate change and water-related diseases[4].

Trauma and acute exacerbations of chronic diseases

Trauma and emergency department (ED) visits

During the acute impact phase of a flood and the subsequent clean-up period, survivors face a high risk of severe physical trauma, including complex orthopedic injuries such as femur and tibial fractures, lacerations, puncture wounds, and hypothermia, which frequently require highly specialized surgical interventions. For example, an analysis of severe casualties from the 2021 flash flood and mudslide disaster in Germany revealed that a single Level I trauma center treated 63 patients, performing 20 complex operations across the spectrum of orthopedic and trauma surgery[22]. The severity of these acute impacts is further reflected in hospital metrics; among these patients, the average Injury Severity Score (ISS) was 5.7±2.7, and the average duration of the hospital stay was 7.2±6.4 days[22]. Emergency healthcare utilization patterns also fluctuate significantly during these crises and are heavily influenced by a community's social vulnerability. An exhaustive analysis of 9,043,518 ED visits in Texas during and following Hurricane Harvey demonstrated that baseline ED visits were 2.03 times higher (95% CI: 1.94–2.11) for census tracts with very high vulnerability compared to the least vulnerable tracts[23]. While overall ED visits tend to decline during and immediately following a flood due to disrupted infrastructure, census tracts characterized by moderate to very high social vulnerability experience significantly smaller declines in utilization compared to the least vulnerable areas[23]. This pattern indicates that highly vulnerable populations, who often lack alternative healthcare access, reliable transportation, or the means to evacuate, are forced to rely heavily on emergency departments for their general healthcare needs, prescription refills, and treatments for acute physical injuries during systemic disaster shocks.

Acute exacerbations of chronic diseases

While disaster response frameworks traditionally prioritize acute physical trauma and infectious disease outbreaks, hydrological disasters trigger severe, prolonged acute exacerbations of pre-existing non-communicable diseases. The flooding mechanism disrupts critical health infrastructure, causing power grid failures, supply chain collapses, and the physical destruction of clinics and pharmacies. This forces an immediate cessation of essential ongoing treatments, such as maintenance hemodialysis, chemotherapy regimens, continuous home oxygen therapy, and daily insulin administration. Compounding these infrastructure failures, the intense acute physical stress and psychological shock of flood events induce systemic neuroendocrine and inflammatory cascades that directly trigger acute cardiovascular and metabolic decompensation[24].

Multi-country epidemiological evaluations reveal that flood inundations cause substantial, statistically significant spikes in hospitalization risks across major chronic non-communicable disease categories. Among these conditions, diabetes mellitus exhibits the highest relative surge, with a 61% increase in hospitalization risk, driven by rapid diabetic ketoacidosis (DKA) and hyperosmolar hyperglycemic state (HHS) admissions resulting from insulin degradation during power blackouts, acute dietary disruption, and stress-induced hyperglycemia[25]. Renal disease hospitalizations similarly increase by 40%, primarily precipitated by missed maintenance hemodialysis sessions when local dialysis facilities suffer structural water damage or power loss; this delayed care rapidly leads to life-threatening hyperkalemia, volume overload, pulmonary edema, and metabolic acidosis[25]. Cardiovascular diseases demonstrate a +35% surge in hospitalizations, as extreme physical exertion during evacuation, cold-water immersion, and acute psychological stress induce sympathetic hyperactivation, precipitating acute myocardial infarctions, decompensated heart failure, hypertensive crises, and stroke[24,25]. Large-scale US cohort analyses by Lynch et al. confirm that heavy rain-related floods are independently associated with a 2.1% increase in

cardiovascular mortality[12]. Furthermore, oncologic conditions experience a 34% increase in hospitalizations stemming from forced interruptions in chemotherapy, radiotherapy, and surgical interventions, alongside severe neutropenic infections from exposure to contaminated floodwaters[25]. Crucially, observational data demonstrate that these elevated chronic disease hospitalization risks are not confined to the immediate impact window, but persist for up to 7 months post-disaster, reflecting prolonged healthcare system recovery timelines and lingering population displacement[25].

Nutritional deficits and food insecurity

Hydrological disasters trigger cascading nutritional crises that extend well beyond the immediate disaster recovery phase. When floodwaters inundate agricultural basins, the physical destruction of standing crops, loss of livestock, contamination of grain storage facilities, and erosion of topsoil lead to immediate agricultural supply shocks. These precipitate severe nutritional crises. This physical destruction is compounded by the collapse of rural transport infrastructure and local market networks, driving rapid regional food price inflation. For agrarian communities reliant on seasonal harvests for both subsistence and income, the loss of agricultural assets instantly eliminates household purchasing power, precipitating severe, prolonged household food insecurity[26].

The health impacts of flood-induced food insecurity are characterized by pronounced gendered disparities and socioeconomic precarity. Women in severely food-insecure households faced more than a threefold increase in the odds of being underweight (BMI <18.5 kg/m^2), yielding an OR of 3.12 (95% CI: 1.68–5.79). Within these severely food-insecure households, the prevalence of underweight status reached a staggering 52.1% (Table 1). This gendered vulnerability stems from both socio-cultural intra-household food allocation dynamics and economic precarity. During severe food shortages, female caregivers frequently reduce their own caloric intake and meal frequency to preserve rations for children and working male family members. When combined with low baseline wealth indices and agricultural dependence, flood-induced food insecurity rapidly exhausts maternal nutritional reserves, driving persistent low body mass index (BMI), maternal anemia, and micronutrient deficiencies[27].

Synthesizing these findings highlights a dangerous biological synergy between post-flood nutritional deficits and infectious disease epidemiology. Protein-energy malnutrition and essential micronutrient deficiencies (e.g., Vitamin a, zinc, iron) severely compromise mucosal barrier integrity and depress T-cell-mediated immune responses[28]. Consequently, undernourished individuals in flooded environments exhibit heightened biological susceptibility to the opportunistic waterborne pathogens (*Vibrio cholerae*, *Shigella*, diarrheal viruses) and zoonotic spirochetes (*Leptospira*) circulating in contaminated floodwaters. This bi-directional interaction creates a destructive feedback loop: food insecurity impairs host immunity, leading to prolonged diarrheal illness, which in turn impairs nutrient absorption and accelerates metabolic wasting[29].

Mitigating the nutritional toll of hydrological disasters requires an integrated, multi-sectoral strategy that bridges social protection, agricultural resilience, and public health interventions. First, targeted gender-responsive social safety nets, including direct cash transfers and nutrient-dense therapeutic food supplementation, must prioritize highly vulnerable pregnant, lactating, and low-BMI women in flood-affected zones. Second, long-term climate-resilient agricultural adaptation should promote flood-tolerant crop cultivars, elevated floating garden bed technologies, and diversified non-agricultural rural livelihoods to safeguard food security against recurring flood events. Finally, integrated WASH-nutrition interventions must co-deploy clean drinking water distribution and point-of-use water purification tablets alongside emergency food distribution to effectively interrupt the destructive malnutrition-diarrhea cycle.

Table 1 Summary of health impacts from flooding and natural disasters

Health outcome category	Specific symptoms or conditions	Key risk factors	Prevalence or magnitude	Impact duration	Source
Mental health	PTSD, depression, anxiety, severe distress, insomnia, panic attacks, nightmares, emotional trauma, isolation	Home damage, displacement, repeat disaster exposure, lower income, lack of social support, female gender, younger age, evacuation, water depth, loss of possessions, secondary stressors (insurance battles, financial hardship)	26–40% for PTSD; 17–22% for depression and 22–30% distress in UK; 52.8% severe depression in Bangladesh (2024); 46% PTSD in Hurricane Harvey survivors	Months to years; can be permanent or chronic in 1/3 of cases	31,32,34,45
Infectious diseases (Gastrointestinal)	Diarrhea, Cholera, Typhoid, Hepatitis A/E, E. coli, Dengue, Salmonella, Shigella, Norwalk virus	Contaminated water/food, failure of WASH infrastructure, sewage overflow, displacement, overcrowding in shelters, skin contact with floodwater, private pond supply	1,346 gastroenteritis cases in Walkerton (2000); 6.9% diarrheal incidence after flooding in Germany (2002)	Post-impact phase (4 days to 4 weeks); can persist up to 2 years	13–15,46
Zoonotic/vector-borne diseases	Leptospirosis (fever, chills, myalgias), Malaria, Dengue, West Nile virus, Zika, Tularemia	Standing water (breeding grounds), contact with floodwater/soil contaminated by rodent urine, lacerated wounds, exposure to livestock, male gender	1,294 cases were positive for Dengue IgM after flooding in Lahore, Pakistan (2010); Leptospirosis OR of flooding contact: 2.19 (meta-Analysis)	Emerges 2–30 days post-exposure; can persist weeks to months	13,16,47
Respiratory outcomes	Asthma exacerbations, bronchitis, pneumonia, ARDS-like syndrome, fungal infections (mucormycosis), toxic pneumonitis	Mold/mildew growth, dampness, aspiration of water (near-drowning), unpermitted air pollution (VOCs, benzene), overcrowding, loss of power for oxygen therapy	20–29% of people were exposed to water-damaged homes after Hurricanes Katrina and Rita, USA	Acute (0–4 days) to months (long-term dampness exposure)	48–50
Physical injury and trauma	Drowning, fractures (lower extremity), lacerations, soft tissue wounds, electrocution, hypothermia, carbon monoxide poisoning	Driving/walking through moving water, cleanup activities, high-velocity debris, structural failure, use of generators in enclosed spaces	Drowning accounts for 75% of flood deaths; 34% of victims required hospitalization, 68% of hospitalized victims required surgery (Germany 2021)	Immediate impact phase to several weeks (cleanup phase)	12,22
Chronic disease/systemic	Diabetes, cardiovascular disease (CVD), renal disease, hypertension, cancer	Interrupted healthcare access, loss of medications (dialysis, chemotherapy), infrastructure damage, stress-induced immune compromise	Hospitalization risk increases: Diabetes (61%), Renal (40%), CVD (35%), Cancer (34%); 2.1% increase in CVD mortality (USA)	Up to 7 months post-event	12,25
Nutritional health	Underweight status (BMI <18.5)	Severe household food insecurity, agricultural dependence, disruption of income, low wealth index	52.1% underweight prevalence in severely food-insecure households	Chronic/persistent	27
Dermatological outcomes	Rashes, skin irritation	Exposure to contaminated floodwaters	–	Immediate impact phase to several weeks	51

WASH=water, sanitation, and hygiene, VOCs=volatile organic compounds, CVD=cardiovascular disease, BMI=body mass index, OR=odds ratio, ARDS=acute respiratory distress syndrome, PTSD=post-traumatic stress disorder, USA=United States, UK=United Kingdom

Psychosocial morbidity

PTSD and acute psychiatric disorders

The acute psychological shock of surviving life-threatening inundations, witnessing community destruction, or undergoing hazardous evacuations drives high rates of acute stress, severe insomnia, panic attacks, and PTSD. A comprehensive meta-analysis of 23 cross-sectional studies revealed that the pooled prevalence of PTSD among flood victims is a staggering 29.48% (95% CI: 18.64–40.31%)[30].

Regional and disaster-specific evaluations highlight even higher acute psychiatric morbidity. Among Hurricane Harvey survivors (USA), the evaluated cohorts exhibited a 46% prevalence rate of PTSD[31]. Severe post-flood depression was documented in 52.8% of affected survivors from flash floods in Bangladesh in 2024[32]. Female gender, younger age, lower household income, and limited social capital serve as key vulnerability drivers that disproportionately heighten post-flood anxiety and depression rates[33].

Involuntary displacement and secondary stressors

Involuntary displacement serves as a primary structural driver of long-term psychological decline. A cross-sectional analysis of UK flood survivors demonstrated that individuals forced to relocate experienced dramatically higher rates of mental health disorders compared to those whose homes were flooded but were not displaced. Specifically, probable PTSD was present in 40% of the displaced group versus 26% of the non-displaced group, anxiety was 30% versus 22%, and depression was 22% versus 17%[34]. Structural equation modeling of involuntary displacement confirms that declines in mental health are driven not just by the primary trauma, but heavily mediated by secondary stressors, such as the loss of social integration and community resources[35].

Compounding trajectories of sequential disaster exposures

Populations are increasingly exposed to sequential, compounding disasters. Longitudinal cohort data tracking Australian populations over ten years (the Household, Income and Labour Dynamics in Australia [HILDA] survey) demonstrated that mental health scores declined by 1.61 points (95% CI: –2.69 to –0.52) during a first disaster exposure[36]. However, upon exposure to a second disaster, the decline was significantly steeper, dropping by 3.37 to 4.52 points[36]. Consequently, the risk of depressive symptoms increased by 3–4% after a first disaster and doubled to 7–8% after a second exposure[36].

This compounding effect demonstrates that cumulative disaster exposures erode psychological resilience, leaving individuals increasingly vulnerable to severe psychiatric decompensation with each subsequent event.

Early warning infrastructure, adaptation systems, and precision public health

As the frequency and spatial unpredictability of climate-driven hydrological disasters accelerate, building health resilience requires transitioning from reactive disaster relief to proactive, climate-resilient adaptation systems. Mitigating the cascading epidemiological, toxicological, and psychological impacts of flooding depends heavily on the integration of MHEWS, digital sensing infrastructure, and targeted precision public health interventions.

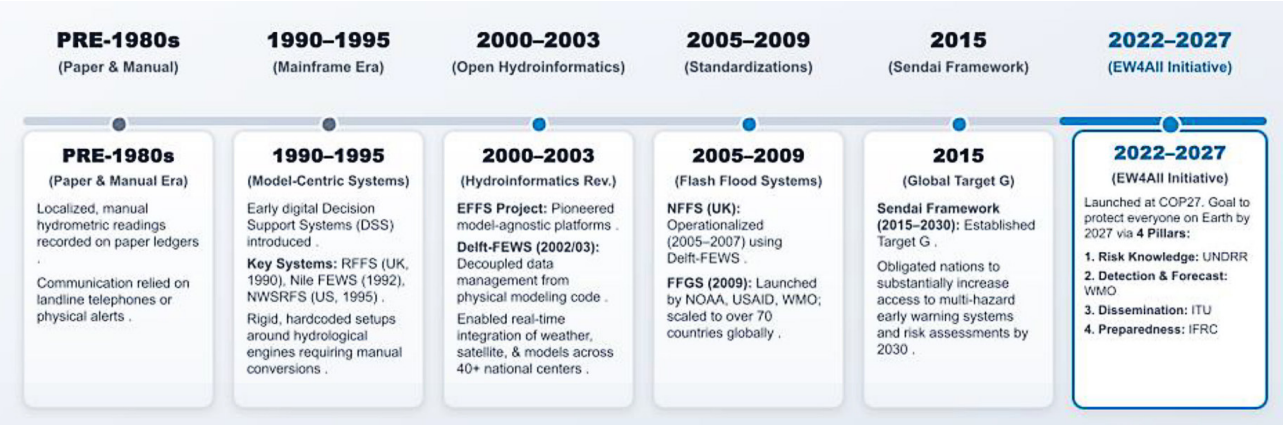
Evolution from single hazard early warning system (EWS) to MHEWS

For over a century, disaster risk monitoring relied on physical records, manual river staff gauges, and analog observation methods (such as floating ball-in-pipe devices or paper-based water level logs)[37]. These

traditional approaches suffered from physical single-copy limits, delayed mail or telegraphic transmission, and severe operational bottlenecks during extreme flooding when observers could not reach gauging stations[38]. In the 1990s, early digital Decision Support Systems were introduced, which included the River Flow Forecasting System (RFFS, 1990) in the UK, the Nile Basin Flood Early Warning System (1992), and the National Weather Service River Forecasting System (NWSRFS, 1995) in the United States, though these legacy setups remained rigid and hardcoded around specific hydrological engines requiring complex manual data conversions[39]. Between 2000 and 2003, the European Flood Forecasting System (EFFS) project pioneered model-agnostic data platforms, leading to the launch of Delft-FEWS in 2002/2003, which decoupled data management from physical modeling code to enable open real-time integration of third-party weather predictions, satellite telemetry, and hydrodynamic models across more than 40 operational centers globally[39]. This open architecture enabled national standardizations such as the UK National Flood Forecasting System (NFFS), operationalized between 2005 and 2007, as well as global deployments like the Flash Flood Guidance System (FFGS) launched in 2009 by the National Oceanic and Atmospheric Administration (NOAA), the United States Agency for International Development (USAID), and the WMO[40]. These technical milestones laid the foundation for global policy mandates, including Target G of the 2015 Sendai Framework for Disaster Risk Reduction obligating nations to substantially increase MHEWS access by 2030, and the UN's EW4All in 2022, which established a universal deadline to protect everyone on earth by 2027 across four functional pillars led by the United Nations Office for Disaster Risk Reduction (UNDRR), the WMO, the International Telecommunication Union (ITU), and the International Federation of the Red Cross and Red Crescent Societies (IFRC)[9]. The timeline of the evolution of EWS to MHEWS is summarized in Figure 1.

Global readiness and modern digital infrastructure

The transition from paper-based, single-basin forecasting to modern MHEWS relies on standardized digital protocols and advanced edge computing architectures.



EFFS=European flood forecasting system, FFGS=flash flood guidance system, IFRC=International federation of the red cross and red crescent societies, ITU=international telecommunication union, MHEWS=multi-hazard early warning systems, NFFS=national flood forecasting system, NWSRFS=national weather service river forecasting system, RFFS=river flow forecasting system, UNDRR=united nations office for disaster risk reduction, USAID=united states agency for international development

Figure 1 The evolution of early warning systems and hydroinformatics

Globally, around two-thirds of WMO members operate continuous 24/7 early warning services year-round, although nearly one-fifth of nations (primarily developing countries and SIDS) still lack continuous 24/7 coverage due to staffing and resource constraints[10]. To standardize digital alerting, adoption of the Common Alerting Protocol (CAP) reached 63% of WMO members globally by 2025, with adoption in Africa reaching 85% following targeted fast-track implementation programs and tools like the CAP Composer[11]. Technical standardization was further elevated when the World Meteorological Congress adopted the Early Warning Services Technical Regulations (EWS-TR), entering into force on January 1, 2027, with a four-year compliance window (2026–2029) to establish baseline global standards for MHEWS design, data exchange, and warning verification[10]. According to a 2025 global report, 119 countries (60% of all countries) now report having a MHEWS, representing a 113% increase over the past 10 years[10]. However, massive coverage gaps persist. Only 43% of SIDS report having systems in place[10].

Regarding modern digital infrastructure: the modern digital EWS deploys non-contact ultrasonic water-level sensors, tipping-bucket rain gauges, and edge/fog microcontrollers that filter noise directly in the field, delivering alert-transmission latencies as low as seconds and maintaining continuous operation during severe weather network disruptions[41]. Complementing this hardware, artificial intelligence (AI) and high-speed analytics, such as neural network hydraulic solvers, execute calculations up to 85 times faster than traditional differential equation solvers while achieving river stage prediction accuracies of up to 96.65%[42].

Life-saving efficacy and socioeconomic effectiveness of MHEWS

Quantitative evaluations across global disaster databases and hydro-economic models highlight the extraordinary return on investment provided by universal MHEWS deployment. The WMO notes that an effective EWS issued within 24 hours can reduce disaster-related damage by 30%[8]. Countries with comprehensive MHEWS experience six to eight times lower disaster mortality compared to unprotected regions, achieving a population protection rate of 93.63% through successful evacuations following early alerts[10]. From an economic perspective, universal MHEWS access avoids approximately $13 billion USD per year in direct capital asset damages and preserves between $22 billion and $31 billion USD annually in household well-being and consumption, reported by the World Bank[43]. With global hydrometeorological EWS maintenance costing roughly $1 billion USD per year, the overall benefit-to-cost ratio exceeds 20:1[43]. Furthermore, providing a 48-hour advance warning enables households and businesses to relocate assets, equipment, and livestock, yielding a greater than 50% reduction in direct damages[10]. To achieve these outcomes, system efficacy is systematically evaluated across six core dimensions: relevance, timeliness, accuracy, accessibility, actionability, and responsiveness.

Prophylaxis and vaccine campaigns

For specific waterborne threats, rapid vaccine deployment is highly feasible. In August 2017, following massive landslides and floods in Freetown, Sierra Leone, that killed over 1,000 people, authorities launched a pre-emptive oral cholera vaccine (OCV) campaign targeting 518,104 people[44]. Post-campaign surveys revealed that the campaign successfully achieved an 82% vaccination coverage for at least one dose and 56% for the full two-dose regimen, successfully averting a widespread post-disaster cholera outbreak[44].

Conclusion

Hydrological disasters represent an escalating, highly complex threat to global public health. As extreme

precipitation events increase, the danger extends far beyond acute drowning and traumatic injury. The post-disaster landscape is characterized by zoonotic outbreaks and severe food insecurity. The enduring legacy of flooding is carried in the severe psychological toll of displacement and compounding trauma. Because these burdens fall disproportionately on the most socially and economically vulnerable populations, building disaster resilience requires sustained investments in MHEWS, resilient infrastructure, and comprehensive psychosocial support.

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