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Review Article

Gateways of aid: Analyzing port performance in disaster relief operations

Dimitris Gavalas*, Ioannis Katsounis and Labros Vasiliadis

Department of Port Management and Shipping, School of Economics and Political Sciences, National and Kapodistrian University of Athens, Greece

Corresponding author's e-mail address: dgaval@pms.uoa.gr

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Abstract

Ports serve as critical nodes in global humanitarian supply chains, enabling the timely delivery of aid during crises. This study examines port performance across 20 major disasters from 2004 to 2023 (including natural catastrophes, health emergencies, and conflicts) using a structured six-dimension analytical framework encompassing infrastructure resilience, customs and bureaucracy, stakeholder coordination, cargo handling, last-mile connectivity, and technological innovation. The research identifies recurring challenges such as infrastructure vulnerabilities, coordination inefficiencies, and bottlenecks in customs clearance, while highlighting adaptive innovations like floating logistics hubs, pre-positioned supplies, and AI-driven coordination systems. Crucially, the analysis incorporates impact awareness of adjacent support stations (including airports and neighboring ports) to assess how regional logistics ecosystems absorb or amplify disruptions. Case studies such as the 2004 Indian Ocean tsunami, the 2022 Ukraine grain initiative, and the 2023 Sudan conflict illustrate how pre-disaster preparedness, regional cooperation, and private-sector engagement shape port effectiveness. The study concludes with actionable recommendations for policymakers, humanitarian organizations, and port authorities, emphasizing investments in resilience, standardized protocols, and multi-stakeholder collaboration to ensure ports remain reliable lifelines in future crises.

1. Introduction

Ports are critical nodes in global supply chains, enabling the movement of goods that sustain economies and communities (Gavalas, 2024). While their commercial role supports trade and industrial activity, disasters require ports to rapidly shift toward humanitarian supply chains, where the priority becomes life-saving aid delivery, rather than economic throughput (Tatham & Houghton, 2011). In such crises, ports act as frontline logistics hubs, and any delay or disruption can jeopardize relief operations. This shift demands high levels of flexibility, coordination, and resilience, particularly when nearby airports or ports must compensate for damaged or overwhelmed facilities. This study investigates the role of ports in humanitarian supply chains by assessing their performance, challenges, and adaptations during major disasters of the 21st century (from the 2004 Indian Ocean tsunami to the 2023 Sudan conflict), highlighting both their essential function and persistent vulnerabilities in preparedness, coordination, and infrastructure resilience.

Although humanitarian logistics research has examined agility, coordination, and resilience during crises (Van Wassenhove, 2006), cross-crisis evaluations of port performance remain limited. Existing studies often focus on single events or technical infrastructure assessments, overlooking the

complex multi-stakeholder dynamics shaping port operations in emergencies. This study addresses that gap by analyzing port functionality across twenty major crises between 2004 and 2023, including natural disasters, pandemics, armed conflicts, and hybrid emergencies, to identify recurring challenges, adaptive responses, and best practices applicable across diverse scenarios.

The research examines case studies across natural disasters, pandemics, and conflicts, identifying recurring issues such as customs clearance bottlenecks, inadequate port infrastructure, and the need for innovative solutions like floating logistics hubs [temporary offshore platforms or repurposed vessels used to receive, store, and transship humanitarian cargo when land-based ports are inoperable, exemplified by the World Food Programme's MV AMC Connector during Cyclone Idai (WFP, 2019)] alongside pre-positioned relief supplies. It also shows how lessons from past crises have informed reforms, including tsunami-resistant port designs, emergency health protocols, and regional cooperation mechanisms. Synthesizing these experiences, the study highlights the need to integrate ports into broader disaster preparedness strategies involving governance reforms, technological upgrades, and multi-stakeholder coordination. It further advocates targeted resilience investments, such as the tsunami-resistant infrastructure introduced in Sri Lanka and Indonesia after the 2004 Indian Ocean tsunami (ADB, 2005; UNESCO-IOC, 2006) and standardized health screening protocols developed following the West Africa Ebola outbreak (WFP, 2015; UNCTAD, 2015), to ensure ports can effectively support humanitarian operations in future crises.

This review aims to inform policymakers at national, regional, and global levels, as well as humanitarian organizations (including UN agencies, international NGOs, and port authorities) on strengthening the efficiency and reliability of humanitarian supply chains so that ports remain essential lifelines during disasters. Its contributions are threefold: (1) a systematic analysis of port performance across diverse disaster typologies, (2) identification of recurring challenges and innovations in humanitarian port logistics, and (3) evidence-based recommendations to enhance port resilience and coordination. Section 2 examines recurring challenges and adaptive strategies, Section 3 presents empirical case studies, Section 4 offers a comparative analysis of port performance, and Section 5 synthesizes policy and operational recommendations. Section 6 concludes with actionable insights for stakeholders.

2. Supply chain management in humanitarian operations

Humanitarian supply chains cover preparation, planning, procurement, transport, storage, tracking, and customs clearance of essential supplies (Thomas & Fritz, 2006; Van Wassenhove, 2006). Unlike commercial logistics, which focus on consumer demand and profit (Tripathi et al., 2024), humanitarian logistics serve beneficiaries without transactional involvement, shifting priorities toward need-based responsiveness, flexibility, and rapid deployment under unpredictable, resource-constrained conditions.

The core objective is timely delivery of goods and services to vulnerable populations, especially in last-mile distribution. A major challenge lies in managing donations from diverse, often inconsistent sources, while minimizing waste and coping with unreliable data (Shrivastav & Bag, 2023). Obstacles include weak infrastructure, bureaucratic inefficiencies, and the involvement of multiple agencies and governments (Malhouni & Mabrouki, 2024). Coordination is further hindered by geopolitical influences, donor stipulations, and lack of unified strategies (Oloruntoba & Gray, 2006). Poor communication and inadequate information sharing exacerbate duplication, misallocation, and delays, particularly in fast-evolving crises where real-time coordination is vital (Shittu et al., 2018; OECD, 2025).

This study examines twenty disaster port responses over the past 20 years, spanning natural disasters, health emergencies, conflicts, and hybrid crises. Natural disasters are analyzed in greater depth to identify standardized procedures for improving humanitarian logistics. Case selection was based on impact scale (casualties, affected populations, geographic scope, resource mobilization) and data availability. The research relies on secondary sources (academic literature, institutional reports,

and verified archives) using content analysis across six dimensions: Infrastructure Resilience, Customs & Bureaucracy, Coordination & Stakeholders, Cargo Handling & Storage, Connectivity & Last-Mile, and Technology & Innovation. These categories, derived from recurring themes and refined through cross-case comparison, balance physical infrastructure with procedural, technological, and coordination factors influencing port performance.

Section 2 outlined humanitarian supply chain principles and challenges, highlighting the need for flexibility, coordination, and efficient resource use. Section 3 builds on this by analyzing global disaster case studies, showing how ports act as critical nodes in humanitarian logistics, while exposing systemic vulnerabilities and innovative adaptations.

3. Global disaster case studies

Table 1 summarizes the key aspects of each disaster case study, focusing on the role of ports, challenges faced, and lessons learned.

Table 1 Key aspects of disaster case studies.

Subsection	Disaster Event	Year	Primary Port(s)	Key Challenges	Innovations/Adaptations	Lessons Learned
Natural Disasters	Indian Ocean Tsunami	2004	Banda Aceh (Indonesia), Colombo & Galle (Sri Lanka)	Complete port destruction; paralyzed relief logistics; coordination failures among 100+ NGOs	USS Abraham Lincoln helicopter airlift; Singapore/Penang as transit hubs; birth of UN Logistics Cluster	Pre-positioned supplies; tsunami-resistant infrastructure; standardized humanitarian cargo protocols
	Great East Japan Earthquake and Tsunami	2011	Sendai, Hachinohe, Ishinomaki, Onahama (Japan)	60 % of Pacific coast ports damaged; 10-meter waves destroyed cranes; radiation fears at Fukushima ports	Temporary roll-on/roll-off facilities within 14 days; port-sharing protocols; AI tsunami warning systems	$12B investment in 14m seawalls; earthquake-absorbing quay designs; regional port mutual aid agreements
	Typhoon Haiyan (Yolanda)	2013	Tacloban (Philippines)	5-meter storm surge destroyed facilities; last-mile distribution “nightmare”; single-port dependency	Amphibious landing craft; Cebu/Surigao as emergency hubs; WFP Logistics Cluster coordination	Higher elevation docks; reinforced breakwaters; regional port diversification; pre-positioned supplies
	Hurricane Maria	2017	San Juan (Puerto Rico), Dominica ports	Complete electrical grid failure; 12-day port operation delay; truck driver shortages	Temporary Jones Act waiver; roll-on/roll-off cargo operations; helicopter airlifts	Microgrid technology; mobile harbor cranes; military-civilian coordination protocols
	Cyclone Idai	2019	Beira (Mozambique)	85 % cargo equipment destroyed; 6m storm surge; grain silo destruction (75 % national reserves)	Floating logistics base (MV AMC Connector); Durban as regional hub via Zimbabwe corridor	$120M elevation investment; stormproof electrical systems; SADC regional stockpiles
	Pakistan Floods	2022	Karachi (Pakistan)	Operational port but 11,000km roads underwater; “world's worst supply chain paradox”	“Brown-water navy” (47 fishing trawlers); floating container stations; ghost port reactivation	Port-to-pakka strategy; 137 secondary riverine access points; amphibious vehicle stockpiling
Health Emergencies	West Africa Ebola Outbreak	2014-2016	Conakry (Guinea), Monrovia (Liberia), Freetown (Sierra Leone)	90 % shipping traffic reduction; 2-day port exit delays; workforce illness/strikes	Dakar regional logistics bases; UN Humanitarian Air Service; fast-track humanitarian lanes	Standardized health screening; dedicated humanitarian cargo corridors; epidemic trade protocols
	COVID-19 Vaccine Distribution	2020-2021	Rotterdam (Netherlands), Dubai (UAE), Mumbai (India)	Ultra-cold chain requirements; equitable distribution challenges; production centralization risks	SmartPort digital tracking; COVAX transshipment hub; multimodal air-sea integration	Cold chain infrastructure criticality; diversified manufacturing needs; public-private partnerships
	Locust Plague (East Africa)	2020	Mombasa (Kenya), Doraleh (Djibouti)	Customs delays for pesticides; phytosanitary check bottlenecks; 1.8M tons crops lost monthly	Locust airbridge; 24-hour emergency clearance lanes; helicopter dispatch stations	Pre-certified pesticide corridors in 12 African ports; temperature-sensitive biopesticide storage; swarm response kits

Table 1 (continued) Key aspects of disaster case studies.

Subsection	Disaster Event	Year	Primary Port(s)	Key Challenges	Innovations/Adaptations	Lessons Learned
Conflicts and Geopolitical Crises	Yemen Conflict	2015-present	Hodeidah (Yemen)	Naval blockade; 70 % import dependency; infrastructure deterioration without maintenance	Pre-clearance system via Djibouti; modular floating fuel terminals; UN deconfliction protocols	UNVIM inspection mechanism; offshore operations capability; cross-faction port worker cooperation
	Ukraine War and Black Sea Grain Initiative	2022-2023	Odesa, Chornomorsk, Pivdennyi (Ukraine)	Russian naval blockade; 20M tons grain trapped; 30 % global wheat price spike	120-mile maritime corridor; Turkish/UN inspection regime; grain trucks on Danube barges	War risk insurance innovations; $50M UN guarantee fund; alternative Danube-Romanian routes
	Sudan Conflict	2023-present	Port Sudan (Red Sea)	Dual civilian-military hub tensions; outdated infrastructure; weeks-long waiting times	Jeddah-Port Sudan maritime corridor; UAE barge-and-truck shuttle; virtual customs clearance	Humanitarian credit swaps; cloud-based clearance platforms; regional surrogate port networks
Hybrid/Complex Emergencies	Haiti Earthquake	2010	Port-au-Prince (Haiti)	Main seaport crippled; only one damaged pier operational; 900+ NGOs operating independently	U.S. military floating piers (JLOTS); massive airlifts; eventual UN logistics cluster coordination	Need for resilient infrastructure; centralized coordination systems; private sector integration
	Refugee Crisis (Mediterranean)	2015	Piraeus, Lesbos (Greece), Lampedusa (Italy), Calais (France)	1M+ asylum seekers; cargo facilities converted to reception centers; disease spread risks	Cruise ships as floating shelters; MSF portable clinics in container yards; mobile processing units	Dedicated humanitarian docks with sanitation; Arabic/Farsi translation materials; culturally appropriate food supplies
	Beirut Port Explosion	2020	Beirut (Lebanon)	2,750 tons ammonium nitrate explosion; 85 % grain reserves destroyed; 80 % import gateways lost	Tripoli/Sidon diversion; WFP mobile grain storage; Cyprus emergency flour supply chain	Governance and safety reforms; alternative port contingencies; regional trade network integration
	Suez Canal Blockage	2021	Global (via Suez Canal)	6-day blockage; 12 % global trade halted; 450+ vessels delayed	Priority rerouting agreements; digital tracking for early delay prediction; air freight switching	Regional stockpiles in Mediterranean/Red Sea; humanitarian cargo priority protocols; Canal alternative routes
Landlocked and Special Cases	Pakistan Floods	2010	Karachi (Pakistan)	20M affected; 700,000 tons aid stuck; roads/rail severed to interior	Multi-modal hub system: port→trucks→trains→helicopters; regional warehouses in Hyderabad/Sukkur	Emergency protocols at Karachi Port Trust; pre-positioned river barges; South-South cooperation models
	Nepal Earthquake	2015	Kolkata (India) - transit port	Landlocked dependency; 1,000km from port; complex India-Nepal transit documentation	Emergency border lanes; pre-positioned stockpiles near transit points; improved India coordination	Fast-track customs for emergencies; dedicated humanitarian staging areas; alternative transit route development
	Guatemala Volcanic Eruptions	2018	Puerto Quetzal (Guatemala)	Pyroclastic flows; 6,000 stranded cruise tourists; simultaneous commercial/humanitarian operations	Container yards for modular housing; grain conveyor repurposed for pumice transport; fishing boats as rescue vessels	Multi-functional port adaptability; heavy-lift capacity for emergency equipment; flexible infrastructure usage
	Turkey-Syria Earthquakes	2023	Iskenderun (Turkey), Mersin (Turkey), Syrian ports	7.8 & 7.5 magnitude quakes; Iskenderun port collapsed and burned; Syria's war-damaged infrastructure	Mersin prioritization; NATO/EU military airlifts; UN cross-border operations from Turkey; Derince as backup	Port system diversification; backup logistics hubs; conflict-zone infrastructure investment; disaster preparedness

Source: Authors' compilation

3.1 Natural disasters

3.1.1 The 2004 Indian Ocean tsunami

The 2004 Indian Ocean tsunami (one of the deadliest disasters in modern history) demonstrated the critical role of ports in humanitarian supply chains and the severe consequences when they are destroyed or mismanaged (World Bank, 2025). Striking without warning on December 26, the tsunami devastated port infrastructure across 14 countries, with Indonesia's Banda Aceh and

Sri Lanka's Colombo and Galle ports among the hardest hit (Harvard Humanitarian Initiative, 2005). In Aceh, waves up to 30 meters destroyed docks, vessels, and cranes, severing the main lifeline for aid to Sumatra's coastline. With roads and airports also damaged, port paralysis created severe bottlenecks that delayed essential relief for millions (Van Wassenhove, 2006). The disaster revealed a stark reality: without functional ports, efficient humanitarian response is impossible, forcing reliance on costly and limited alternatives such as airdrops and amphibious landings (US Marine Corps, 2025; Telford & Cosgrave, 2006).

Improvised recovery efforts exposed both ingenuity and systemic weaknesses. The U.S. Navy's USS Abraham Lincoln carrier group provided emergency airlift capacity, but even this could not match the throughput of a functioning port (U.S. Navy, 2005). Undamaged regional ports such as Singapore and Penang became vital transit hubs, yet poor coordination led to congestion and mismanaged cargo flows, with unlabeled aid accumulating alongside commercial shipments (Thomas & Fritz, 2006). The UN's early Logistics Cluster struggled to coordinate hundreds of independent NGOs and military actors, resulting in duplicated efforts and inappropriate donations (Balcik et al., 2010). These challenges prompted reforms, including pre-positioned relief stocks in strategic ports and standardized humanitarian cargo-prioritization protocols (OCHA, 2007).

The tsunami's legacy reshaped port integration into disaster preparedness. Sri Lanka rebuilt ports with tsunami-resistant breakwaters and elevated storage areas, while Aceh became a model for rapid-response port rehabilitation (UNEP, 2007; ADB, 2005). The disaster also catalyzed the Indian Ocean Tsunami Warning System to reduce future disruptions (UNESCO-IOC, 2006). Most importantly, it underscored the need for pre-disaster port resilience investments, affirming that maritime infrastructure in coastal nations is not only an economic asset, but a humanitarian safeguard (Pettit & Beresford, 2009). This directly aligns with the study's core research gap: the limited integration of ports into disaster preparedness frameworks and the absence of standardized resilience benchmarks tailored to humanitarian logistics.

3.1.2 The 2011 Great East Japan Earthquake and Tsunami

The 2011 Great East Japan Earthquake and Tsunami was a major test of port resilience, as the 9.0-magnitude quake and ensuing waves devastated 60 % of Japan's Pacific coastline and critical port infrastructure (MLIT, 2011). Sendai Port suffered catastrophic losses, with 10-meter waves destroying terminals, cranes, and vessels, while 15 major commercial ports (handling 7 % of national trade) were rendered inoperable, causing an estimated $3.4 billion in daily economic disruption (UNESCAP, 2013; Hosseini et al., 2016). The collapse of these ports created a humanitarian crisis for 470,000 displaced survivors, forcing the Self-Defense Forces to establish a sea-and-air bridge using undamaged western ports such as Fukuoka and Osaka (Koshimura & Shuto, 2015).

Japan's response revealed both vulnerabilities and strong adaptive capacity. Operations at the Fukushima-adjacent Port of Soma were halted due to radiation concerns, shifting relief to Hitachinaka (Ishii et al., 2011). Engineers restored partial functionality at Sendai within 14 days using temporary roll-on/roll-off facilities, enabling initial humanitarian shipments (MLIT, 2011). The disaster triggered major reforms, including $12 billion in seawalls, earthquake-absorbing quay structures, and AI-enabled tsunami warning systems (Wang et al., 2022), as well as innovative "port-sharing" protocols to ensure rapid traffic redistribution when facilities fail (UNDP, 2014).

3.1.3 The 2013 Typhoon Haiyan (Yolanda) in Philippines

Typhoon Haiyan (Yolanda) in November 2013 exposed the extreme vulnerability of Philippine port logistics and the immense effort required to restore humanitarian supply chains. The Category 5 storm devastated key Eastern Visayas ports (especially Tacloban, the region's main gateway) destroying nearly all cargo-handling equipment and washing several vessels inland (OCHA, 2013). With berthing facilities ruined and access roads blocked, relief operations were delayed by up to 10 days, severely restricting aid flows to more than 14 million affected people (World Bank, 2014;

Loquinte et al., 2015). The simultaneous collapse of roads and airports compounded the bottleneck, making the port's paralysis a central constraint on the early response.

Rapid rehabilitation became essential. The Philippine government, supported by the U.S. military and WFP, cleared debris and wrecked ships from Tacloban's harbor (WFP, 2014). Naval vessels such as the USNS Charles Drew delivered supplies via amphibious craft, bypassing damaged infrastructure. Secondary ports like Cebu and Surigao were repurposed as emergency hubs, though congestion quickly emerged due to limited capacity (van Wassenhove & Pedraza Martinez, 2012). The Logistics Cluster established temporary storage and coordinated cargo prioritization, yet last-mile delivery remained severely hindered by destroyed roads, fuel shortages, and security challenges.

3.1.4 The 2017 Hurricane Maria (Puerto Rico & Caribbean)

Hurricane Maria's landfall in Puerto Rico in September 2017 underscored the critical importance of port infrastructure for island nations. The Category 4 storm devastated the island's logistics network, with the Port of San Juan (responsible for 90 % of inbound cargo) suffering severe damage to cranes, storage yards, and electrical systems (US Army Corps of Engineers, 2017). Flooding, storm surge, and toppled containers created a debris field that took weeks to clear, while the collapse of the electrical grid left 3.4 million residents without power, water, or reliable access to essential goods. The port's paralysis triggered cascading failures across the island's just-in-time supply chain, affecting hospitals, fuel distribution, and food availability (FEMA, 2017).

The federal response revealed major shortcomings in emergency port management. Although the U.S. military eventually established temporary operations, a 12-day delay in restoring full port functionality significantly slowed the delivery of life-saving supplies, worsening shortages in remote areas (US Army Corps of Engineers, 2017). With gantry cranes inoperable, cargo had to be rolled directly from ships to trucks, a process five times slower than normal. A severe shortage of truck drivers (many personally affected by the disaster) further constrained distribution (FEMA, 2017), highlighting the vulnerability of post-disaster logistics to disruptions in local transport labor and assets. Strengthening resilience therefore requires contingency planning for ground transport continuity, including mutual-aid agreements, mobile fleets, and rapid-activation third-party logistics support. The crisis also prompted a temporary waiver of the Jones Act to ease supply shortages, while smaller Caribbean islands such as Dominica faced even greater challenges, relying on helicopter and amphibious deliveries after their port facilities were destroyed (UN OCHA, 2017).

3.1.5 The 2019 Cyclone Idai (Mozambique)

Cyclone Idai's landfall in March 2019 exposed the fragile dependence of coastal developing nations on port infrastructure, most visibly through the paralysis of Beira Port, which halted the delivery of food, medical supplies, and fuel to over 1.85 million people and cut access to Mozambique's main wheat reserves (UNDP, 2019). Winds of 175 km/h and a 6-meter storm surge submerged container yards, short-circuited electrical systems, and disabled 85 % of cargo-handling equipment, shutting down a port that normally handled 90 % of central Mozambique's imports (WFP, 2019). The destruction of nearby grain silos (holding 75 % of national wheat reserves), combined with flooded access roads from Maputo, triggered acute shortages and heightened malnutrition risks across multiple provinces (FAO, 2019).

The humanitarian response demonstrated both innovation and systemic vulnerability. Within 72 hours, WFP deployed a floating logistics base using repurposed offshore vessels; the MV AMC Connector functioned as a temporary deep-water port, enabling lightering operations when land-based facilities were unusable (WFP, 2019). South Africa's Port of Durban became a regional hub, moving 18,000 metric tons of relief cargo in six weeks, though at quadruple normal costs due to long-distance overland transport (UNDP, 2019). The crisis also revealed Mozambique's dependence on a single port: when Beira's fuel terminal failed, hospitals across four provinces lost generator

capacity within days, underscoring how port disruptions directly affect medical outcomes (WFP, 2019).

Idai's legacy prompted major resilience investments, including $120 million to elevate Beira's infrastructure, install stormproof electrical systems, and build elevated emergency terminals (FAO, 2019). Regionally, SADC established pre-positioned relief warehouses in strategic ports such as Walvis Bay and Dar es Salaam to strengthen future disaster response capacity (SADC, 2019).

3.1.6 The 2022 Pakistan floods

The 2022 Pakistan floods, which submerged one-third of the country, exposed both the importance and limitations of port infrastructure in climate-driven mega-disasters. Although Karachi Port remained fully operational, it became largely ineffective for inland relief because 11,000 km of highways and railways were underwater, creating what UN officials called "the world's worst supply chain paradox" (UN OCHA, 2022). With 33 million people displaced, the military improvised a "brown-water navy," converting 47 fishing trawlers into shallow-draft aid barges capable of navigating flooded terrain where helicopters could not operate (Pakistan Navy, 2022).

The crisis triggered major innovations in decentralized port logistics. The small river port of Sukkur became a humanitarian hub, transferring aid from trucks to amphibious vehicles and even camels, while floating container-unpacking stations enabled supplies to be broken down for distribution via fishing boats (World Bank, 2022). The reactivation of long-abandoned British-era river terminals in Punjab further demonstrated the value of "ghost ports" when modern infrastructure collapses.

The floods also revealed major gaps in climate adaptation for South Asian ports. Despite Karachi's high-capacity cranes, inland distribution failures made last-mile delivery the decisive bottleneck. In response, Pakistan's NDMA introduced a "port-to-pakka" strategy, identifying 137 secondary riverine access points and stockpiling portable unloading equipment (NDMA, 2022). The disaster also accelerated the use of amphibious trucks in regional responses and informed new WHO protocols for floating medical clinics.

3.2 Health emergencies

3.2.1 The 2014 - 2016 West Africa Ebola Outbreak

During the 2014 - 2016 Ebola outbreak, ports became both essential lifelines and major choke points in Guinea, Liberia, and Sierra Leone. Shipping traffic to Conakry, Monrovia, and Freetown collapsed as vessels diverted to alternative ports, even as these facilities remained critical entry points for medical supplies and humanitarian aid (UNCTAD, 2015; World Bank, 2016). Enhanced screening, disinfection protocols, and workforce shortages turned ports into bottlenecks, delaying offloading and distribution and highlighting the need for contingency measures that balance public health safeguards with uninterrupted aid flows (WFP, 2015a).

The economic consequences were severe. With shipping activity reduced by up to 90 %, port throughput plummeted, disrupting essential imports of food, fuel, and medicines. Clearance delays, limited storage, and last-mile distribution failures slowed operations dramatically; in Monrovia, trucks carrying PPE waited two days to exit the port. Labor disruptions (dockworker illness, refusals to work without hazard pay, and strikes in Freetown) further exposed the absence of workforce-continuity planning during health emergencies, contributing to the region's $2.8 billion in economic losses (World Bank, 2016).

Humanitarian actors responded with adaptive solutions. WFP established regional logistics bases in Dakar, while the UN Humanitarian Air Service provided costly airlifts when maritime routes faltered. The crisis ultimately revealed major gaps in port preparedness for epidemics, prompting new international guidelines, including fast-track lanes for humanitarian cargo and standardized health-screening protocols for port workers (WFP, 2015).

3.2.2 The COVID-19 vaccine distribution

During the COVID-19 vaccine rollout, global ports became essential enablers of pandemic logistics. Rotterdam, Dubai, and Mumbai each played distinct roles in sustaining global immunization under strict time and temperature constraints. Rotterdam (the EU's primary vaccine gateway) leveraged extensive cold-storage capacity and its SmartPort digital tracking system to process millions of temperature-sensitive doses with real-time integrity monitoring, coordinating closely with Pfizer and Maersk to maintain a seamless cold chain during the critical early 2021 period (Port of Rotterdam, 2021; Gavalas et al., 2022). This case illustrates how pre-existing infrastructure, digital integration, and public-private coordination strengthen port resilience for health emergencies.

Dubai's Jebel Ali Port and the adjacent International Humanitarian City served as the central redistribution hub for COVAX shipments to more than 100 low- and middle-income countries across Africa, South Asia, and the Middle East (USAID, 2021). Advanced cold-chain facilities, efficient customs procedures, and the integration of DP World's port operations with Emirates SkyCargo created a multimodal system capable of rapid, temperature-controlled delivery to regions with limited storage capacity (DP World, 2021; Emirates SkyCargo, 2021).

Mumbai Port, home to the Serum Institute of India, functioned as both a manufacturing hub and export gateway for Covishield, moving millions of doses across Asia, Africa, and Latin America. However, India's Delta-driven export bans in 2021 exposed the vulnerability of centralized production models and underscored the need for geographically diversified vaccine manufacturing and distribution networks (Gavalas, 2025). Collectively, these cases show how maritime infrastructure can determine the success of global health responses: Rotterdam demonstrated the value of technological integration, Dubai highlighted the importance of strategic transshipment hubs, and Mumbai revealed both the strengths and risks of concentrated vaccine production (Port of Rotterdam, 2021; DP World, 2021; Serum Institute of India, 2021).

3.2.3 The 2020 Locust Plague (East Africa)

The 2020 East Africa locust plague (the worst in 70 years) turned regional ports into critical food-security battlegrounds as swarms consumed 1.8 million metric tons of crops per month across Kenya, Somalia, and Ethiopia (FAO, 2020). Mombasa Port, responsible for 80 % of East Africa's agricultural imports, became the crisis hub, yet delays in clearing pesticides and spray equipment had severe consequences. With swarms capable of covering 2,400 km² daily, each hour of port congestion translated into thousands of hectares of crop loss (UNICEF, 2020). Customs bottlenecks, especially for organophosphate pesticides requiring strict phytosanitary checks, left shipments stalled for weeks, contributing to acute food insecurity affecting 35 million people (WFP, 2020).

The response introduced new agro-logistics models. FAO created a "locust airbridge" via Mombasa's airport to bypass port delays, while Kenya implemented 24-hour emergency clearance for pest-control equipment (FAO, 2020). Djibouti's Doraleh Port was repurposed as a secondary staging ground for helicopter-based biopesticide deployment, and Mombasa later hosted a regional satellite-based locust monitoring center to enable pre-positioning of supplies (UNICEF, 2020).

The crisis permanently reshaped port practices for agricultural emergencies. Reforms included pre-certified pesticide corridors with fast-track customs clearance (now adopted in 12 African ports), dedicated storage zones for temperature-sensitive biopesticides, and port-based "swarm response kits" for rapid frontline deployment (FAO, 2020).

3.3 Conflicts and geopolitical crises

3.3.1 The 2015 Yemen conflict

The 2015 Yemen conflict turned national ports into both humanitarian lifelines and strategic battlegrounds. With land borders closed, Hodeidah (normally handling 70 % of Yemen's imports) became the sole entry point for 90 % of the country's food, fuel, and medical supplies, assuming life-or-death importance as 20 million Yemenis faced famine (HRW, 2017). A Saudi-led naval

blockade, imposed over weapons-smuggling concerns, left vessels waiting weeks for inspection while malnutrition rates surged (WFP, 2019).

Operational conditions at Hodeidah illustrated the extreme difficulty of sustaining port functions in active conflict zones. Infrastructure deteriorated rapidly: cranes failed, dredging ceased, silt accumulated, and the electrical grid collapsed repeatedly (Logistics Cluster, 2017). Humanitarian workers reported insulin spoiling on docks, wheat rotting in damaged silos, and fuel shortages halting inland transport (Oxfam, 2018). A partial solution emerged through the UN Verification and Inspection Mechanism (UNVIM), which screened cargo before arrival to maintain minimal supply continuity (UNVIM, 2019).

The crisis generated lasting innovations in conflict-zone port management. WFP introduced a Djibouti-based "pre-clearance" system that cut vessel wait times from weeks to days (WFP, 2019). Engineers developed modular floating fuel terminals to operate offshore when onshore facilities were damaged or contested (UNOCHA, 2018). Most notably, new UN-supervised "deconfliction" protocols enabled port workers from opposing factions to collaborate in maintaining essential infrastructure; an approach later adapted in Ukraine's Black Sea grain initiative (UN News, 2022).

3.3.2 The 2022 Ukraine War and Black Sea Grain Initiative

The 2022 war in Ukraine triggered a global food security crisis by placing Ukraine's Black Sea ports at the center of geopolitical tension. Russia's blockade of Odesa, Chornomorsk, and Pivdennyi trapped 20 million tons of grain in silos, driving global wheat prices up 30 % and threatening severe shortages across the Middle East and Africa, where countries such as Somalia, Yemen, and Lebanon relied on Ukrainian grain for over half of their imports (FAO, 2022). With Ukraine normally supplying 10 % of global wheat and 15 % of global corn, the port closures translated directly into rising hunger for 44 million people worldwide.

The UN-Türkiye–brokered Black Sea Grain Initiative in July 2022 created a 120-nautical-mile maritime corridor that allowed grain exports to resume under joint inspections by UN, Turkish, and Russian officials (UN, 2022). Over its year-long operation, the initiative enabled 33 million metric tons of exports (65 % to developing nations) despite crews in Odesa working under air-raid sirens and missile threats. Its success relied on specialized war-risk insurance and a $50 million UN guarantee fund to protect shipowners (IMO, 2022).

Yet the initiative also exposed the fragility of humanitarian port operations in conflict zones. Russia's repeated threats to withdraw, culminating in July 2023, destabilized shipping and insurance markets. Direct attacks on port infrastructure (including the destruction of 60,000 tons of grain in Odesa in May 2023) further underscored the vulnerability of maritime supply chains. Alternative land routes through Europe handled only a fraction of Ukraine's capacity at triple the cost, demonstrating the irreplaceable role of high-volume seaports in global food security (World Bank, 2023). The crisis also spurred logistical innovation, such as Ukraine's "grain trucks on barges" moving exports via the Danube to Romanian ports when Black Sea access was uncertain (WFP, 2023).

3.3.3 The 2023 Sudan Conflict

The 2023 Sudan conflict turned Port Sudan into both a humanitarian lifeline and a geopolitical flashpoint. With Khartoum paralyzed and land routes severed, the port became Sudan's last major operational gateway for aid to 25 million people, underscoring the need for contingency planning, alternative routing, and close coordination with humanitarian actors in protracted conflicts. Handling 90 % of national imports, the port's dual civilian–military role created severe tensions: WFP vessels carrying Ukrainian wheat docked alongside weapons shipments, and relief ships waited weeks for security clearances amid artillery fire near grain silos (de Araujo Grigoli et al., 2024).

Outdated infrastructure and heightened security protocols compounded congestion. Designed for larger vessels but receiving smaller ships, Port Sudan faced weeks-long delays, with 120,000 tons of food and medical supplies stalled as customs demanded extensive documentation. These

bottlenecks worsened hunger and disease as essential goods remained trapped in port facilities (UNHCR, 2023).

Humanitarian actors developed costly workarounds. The UN opened a maritime corridor from Jeddah requiring armed escorts, while the UAE launched a "barge-and-truck" shuttle from Fujairah to small Sudanese fishing harbors. Airdrops from Djibouti cost $13,500 per metric ton (compared to $150 via normal port operations) highlighting the immense cost of bypassing traditional logistics during conflict (de Araujo Grigoli et al., 2024). Fuel supply chains also collapsed. Damage to the Port Sudan refinery forced agencies to truck fuel 2,000 km from Chad to keep hospitals and water systems functioning, revealing the extreme vulnerability of energy logistics in conflict zones (UNHCR, 2023).

Despite these challenges, innovative solutions emerged. "Virtual customs clearance," developed by Sudanese tech startups, enabled digital processing of humanitarian cargo when physical administration failed, offering a scalable model for fragile states. WFP also used "humanitarian credit swaps" to prepay port fees and accelerate relief shipments. Most importantly, the crisis highlighted the growing role of regional ports as humanitarian surrogates when primary ports militarize or collapse. Egypt's Ain Sokhna and Eritrea's Massawa became critical gateways for aid, demonstrating the value of flexible, decentralized, and improvisational logistics networks in active conflict environments (UNHCR, 2023).

3.4 Hybrid/Complex emergencies

3.4.1 The 2010 Haiti earthquake

The 2010 Haiti earthquake starkly illustrated both the importance of functional port infrastructure and the chaos that ensues when it fails. When the 7.0 magnitude quake struck, it crippled Port-au-Prince's main seaport, destroying cranes, collapsing warehouses, and leaving only one damaged pier operational (Balcik et al., 2010). This single point of failure created catastrophic bottlenecks, forcing relief ships to wait weeks to unload while lives hung in the balance (Van de Walle & Dugdale, 2012). The international response revealed innovative workarounds, including U.S. military floating piers (JLOTS) and massive airlifts, but these were costly temporary fixes that underscored the need for resilient port infrastructure (GAO, 2011).

Coordination challenges during the Haiti crisis exposed systemic weaknesses in humanitarian logistics. With over 900 NGOs operating independently, duplicate shipments and mismatched aid flooded the compromised port while essential supplies languished (Binder & Grunewald, 2010). The absence of centralized control led to infamous examples of wasted resources (i.e., winter coats arriving in the tropical climate), while security breakdowns allowed looting to further disrupt supply lines (OCHA, 2010). The eventual establishment of UN-coordinated logistics clusters and humanitarian staging areas helped streamline operations, but these reactive measures came too late for many victims. Private sector partners proved invaluable in restoring operations, yet tensions arose between commercial priorities and humanitarian imperatives (Tatham & Houghton, 2011).

3.4.2 The 2015 Refugee Crisis (Mediterranean)

The 2015 Mediterranean refugee crisis turned Southern European ports into critical humanitarian waystations as over one million asylum seekers (mainly from Syria, Afghanistan, and Iraq) arrived in facilities built for cargo rather than human care (UNHCR, 2016). Greek ports such as Piraeus and Lesbos processed up to 10,000 people daily, converting car parks and warehouses into makeshift reception centers, while the small fishing port of Molyvos became an improvised triage site for exhausted arrivals (IOM, 2015).

The crisis exposed major gaps in port preparedness for mass-migration emergencies. Most ports lacked medical screening capacity, leading to overcrowding and rapid disease transmission; in Lampedusa, a single bathroom served thousands for weeks (ECRE, 2016). Responses relied heavily on improvisation; cruise ships repurposed as floating shelters, MSF clinics set up in container yards, while security measures, such as razor-wire fencing in Calais, often clashed with humanitarian needs

(Amnesty International, 2016). These events permanently reshaped port protocols in transit zones. EU-funded reforms introduced dedicated humanitarian docks with sanitation facilities, mobile processing units for faster registration and health checks, and pre-positioned emergency kits with translation materials and culturally appropriate food (European Commission, 2017).

3.4.3 The 2020 Beirut Port Explosion (Lebanon)

The August 4, 2020 Beirut port explosion (caused by the detonation of 2,750 tons of ammonium nitrate) killed 218 people, injured 7,000, and destroyed the port's grain silos holding 85 % of Lebanon's reserves, along with key container terminals and cargo-handling equipment (UN, 2020). As Lebanon's primary maritime gateway handling 80 % of national imports, the port's collapse triggered a compound crisis: medical supplies could not be unloaded, wheat imports stalled, and the already fragile economy edged toward collapse (WFP, 2020). The disaster exposed Lebanon's extreme dependence on a single port, with no viable contingency routes or inland redundancies to maintain food and medical supply chains.

In the aftermath, large vessels were diverted to smaller ports such as Tripoli and Sidon, which had only a fraction of Beirut's handling capacity and lacked prioritization mechanisms for relief cargo. These facilities also suffered from limited grain storage, inadequate cold-chain capacity, and insufficient equipment for humanitarian shipments. Bureaucratic delays further compounded the crisis, with emergency aid stuck in customs despite waived restrictions (UN, 2020). WFP deployed temporary mobile grain storage near Tripoli and coordinated flour imports through Cyprus, illustrating how port destruction can disrupt regional trade networks (WFP, 2020).

The explosion also revealed deep governance failures. Investigations showed the ammonium nitrate had been negligently stored for six years despite repeated warnings, highlighting systemic corruption in port administration. The resulting economic collapse (currency depreciation of 90 %, soaring inflation, and tenfold increases in food prices) demonstrated how port governance failures can escalate into nationwide humanitarian crises (HRW, 2020). Humanitarian agencies responded with workarounds such as direct cash assistance and reliance on alternative regional ports to bypass Lebanon's paralyzed supply chains.

3.4.4 The 2021 Suez Canal Blockage (Global Ripple Effects)

The 2021 Suez Canal blockage by the Ever Given created global ripple effects across humanitarian supply chains, revealing how disruptions at maritime chokepoints can indirectly hinder life-saving aid operations. For six days, the grounded vessel halted 12 % of global trade and delayed more than 450 ships (UNCTAD, 2021). Although not a traditional disaster, the incident exposed vulnerabilities in just-in-time systems relied upon by humanitarian actors. European ports such as Rotterdam and Antwerp experienced delays in Syrian refugee aid shipments, while in Jeddah, containers of COVID-19 vaccine components remained stranded, threatening inoculation campaigns in East Africa (Nesterenko et al., 2024).

Temperature-sensitive humanitarian cargo was particularly affected. Insulin bound for Yemen was trapped in the Mediterranean, forcing costly emergency procurement from Dubai, and delayed Ukrainian wheat shipments contributed to cereal price spikes in Sudan. The crisis underscored how humanitarian logistics are deeply intertwined with commercial shipping networks, as NGOs depend on the same container lines for 60 % of their discounted cargo movements.

In response, agencies introduced new contingency measures. The UN established regional stockpiles of high-demand relief items in Mediterranean and Red Sea ports, while shipping companies created priority rerouting agreements for humanitarian cargo. The incident also accelerated adoption of digital tracking tools, enabling earlier delay detection and timely shifts to air freight when necessary (World Economic Forum, 2021).

3.5 Landlocked and special cases

3.5.1 The 2010 Pakistan Floods

The 2010 Pakistan floods submerged an area larger than England, affected 20 million people, and caused $10 billion in damages. As the Indus River swelled to 40 times its normal volume, the Port of Karachi became the central hub for 90 % of incoming aid, yet its commercial-oriented terminals were quickly overwhelmed by relief shipments (WFP, 2010). With road and rail links severed, 700,000 tons of emergency supplies accumulated in port yards while victims in Punjab and Khyber Pakhtunkhwa waited weeks for assistance (Balcik & Beamon, 2008).

Multiple bottlenecks compounded the crisis. Karachi lacked emergency customs protocols, leaving critical items like water purification tablets stuck in paperwork. Equipment shortages and an unprepared workforce slowed cargo handling, while flooded trucking routes forced aid agencies to improvise a multi-modal chain: trucks to railheads, trains across damaged corridors, and military helicopters for last-mile delivery (WFP, 2010). This system moved 50,000 metric tons monthly but at triple normal cost (Van Wassenhove & Pedraza Martinez, 2012).

The disaster exposed major gaps in Pakistan's port-centric preparedness. Karachi had no dedicated humanitarian staging areas, no fast-track customs clearance, and no contingency plans for inland distribution when primary routes failed. Post-flood reforms introduced emergency protocols at Karachi Port Trust, pre-positioned river barges, and established regional warehouses in Hyderabad and Sukkur. The crisis also informed South-South cooperation, inspiring Indonesia and Türkiye to develop port-to-disaster-zone response models based on Pakistan's experience (ALNAP, 2012).

3.5.2 The 2015 Nepal Earthquake

The 2015 Nepal earthquake underscored the critical importance of port logistics for landlocked countries. With Nepal's infrastructure severely damaged (including roads and Kathmandu's only international airport) the country became entirely dependent on India's Kolkata Port, more than 1,000 km away, as the primary gateway for relief supplies (Shrestha & Pathranarakul, 2018; UNOCHA, 2015). The port was quickly overwhelmed as thousands of tons of aid arrived simultaneously, creating major customs bottlenecks exacerbated by Nepal's complex transit agreement with India, which required extensive documentation for every shipment (WFP, 2015b; UNDP, 2016).

Critical supplies such as tents, medical equipment, and food rations remained stranded in Kolkata for weeks due to bureaucratic delays, overcrowded storage yards, and insufficient transport capacity (World Bank, 2015). Many relief organizations, unfamiliar with Nepal's reliance on transit ports, shipped materials without proper paperwork, worsening congestion (Shrestha & Pathranarakul, 2018). The single highway linking Kolkata to Kathmandu became clogged with trucks, delaying time-sensitive medical deliveries, while the absence of emergency port-prioritization protocols meant humanitarian cargo competed with commercial shipments (UNOCHA, 2015; UNDP, 2016).

The earthquake exposed systemic weaknesses in Nepal's logistics preparedness, including the lack of humanitarian staging areas at border points, fast-track customs procedures, and inter-agency coordination (World Bank, 2015). Post-crisis reforms introduced emergency lanes at border crossings, prepositioned stockpiles near transit points, and improved coordination with Indian port authorities. The disaster also spurred regional discussions on diversifying transit routes through neighboring countries to reduce dependence on a single port in future emergencies (Shrestha & Pathranarakul, 2018).

3.5.3 The 2018 volcanic eruptions in Guatemala

The 2018 volcanic eruptions of Guatemala's Volcán de Fuego (June 3 - 7) created an unprecedented logistical crisis that transformed Puerto Quetzal, the country's largest Pacific port, into a multi-functional disaster hub. When the volcano's pyroclastic flows buried entire villages under superheated ash and debris, the port's infrastructure was abruptly repurposed to handle challenges

never anticipated in its commercial design. The facility's 14-meter-deep berths, normally receiving fruit carriers and cruise ships, instead accommodated specialized emergency vessels carrying volcanic monitoring equipment from the U.S. Geological Survey and Japan's International Cooperation Agency (USGS, 2018). The port's vast container yards became staging areas for assembling modular temporary housing, while its vehicle ramps were adapted to load helicopters with thermal imaging drones for search missions in still-smoldering disaster zones.

What made this port's humanitarian role extraordinary was its simultaneous management of competing priorities. While processing incoming aid shipments (including 40,000 emergency hygiene kits from UNICEF), the port also had to evacuate 6,000 stranded tourists from diverted cruise ships, using its passenger terminals as temporary shelters. Engineers leveraged the port's heavy-lift capabilities to handle lava-resistant road construction equipment for rebuilding routes to isolated communities. The crisis revealed innovative adaptations: the port's grain conveyor system was repurposed to load pumice stone onto trucks for erosion control in downstream villages, while fishing boats, normally used for cargo lighters, became amphibious rescue vehicles in flood-prone areas where ash had altered river courses (USGS, 2018).

3.5.4 The February 2023 earthquakes in Türkiye and Syria

The February 2023 earthquakes in Türkiye and Syria (M7.8 and M7.5) revealed how indispensable yet fragile ports are in humanitarian supply chains. Iskenderun Port (one of the region's key logistics hubs) collapsed during the tremors, and fires from overturned containers burned for days, forcing aid agencies to reroute shipments through Mersin over 200 km away. This diversion slowed the delivery of rescue equipment, winter shelters, and medical supplies. In Syria, where port capacity had already been degraded by years of conflict, the earthquakes intensified existing logistical constraints, leaving humanitarian actors dependent on fragile cross-border land routes (Bassal et al., 2024).

The emergency response underscored the need for resilient and flexible port systems. With Iskenderun inoperable, Türkiye prioritized aid flows through Mersin, while NATO and the EU organized military airlifts to Adana. UN agencies, including the World Food Programme, relied on pre-positioned regional stocks to accelerate distributions. Yet overlapping shipments caused congestion, customs delays slowed critical equipment, and political disputes complicated cross-border operations into Syria. Türkiye's rapid shift to Derince Port demonstrated the value of backup hubs, while Syria's difficulties highlighted the consequences of long-term neglect of maritime infrastructure (Kaneda & Akashima, 2023).

All of the above case studies reinforced broader lessons for humanitarian port logistics. Infrastructure resilience is paramount: ports require disaster-resistant breakwaters, elevated storage yards, and protected electrical systems to remain operational during crises. Coordination mechanisms, such as UN-led logistics clusters, help prevent duplication and streamline cargo prioritization. Flexibility (including temporary floating ports, amphibious vehicles, and repurposed equipment) can overcome damaged infrastructure and congested routes. Preparedness, through pre-positioned supplies and designated backup hubs, accelerates response times. Finally, governance weaknesses (corruption, bureaucracy, and absent emergency plans) can magnify crises, as seen in Beirut and Sudan. Strengthening port governance, emergency procedures, and public-private coordination is essential for building resilient humanitarian supply chains.

4. Comparative analysis of port performance in humanitarian supply chains

The evaluation of natural disaster response operations examined in this study revealed systemic challenges in the preparation and execution of humanitarian logistics processes. Even in cases with pre-established contingency plans, deficiencies in logistical training impeded initial response efforts, resulting in critical delays. These identified shortcomings represent actionable opportunities for enhancement and merit further scholarly investigation. Conversely, the observed

operational successes exemplify best practices that may serve as foundational models for future humanitarian interventions.

To systematically categorize these findings, a thematic content analysis was conducted, distinguishing between areas requiring improvement (problems) and exemplary practices (positives). The synthesized results of this analytical phase are presented in **Table 2**.

Table 2 Research topics in humanitarian logistics based on port-centric case studies.

Subsection	Disaster Event	Problems	Positives
Natural Disasters	Indian Ocean Tsunami (2004)	Port infrastructure destroyed; coordination chaos with 100+ NGOs; inappropriate donations (winter clothing to tropics); unlabeled shipments	USS Abraham Lincoln helicopter operations; Singapore/Penang transit hubs; birth of UN Logistics Cluster; pre-positioned supplies strategy
	Great East Japan Earthquake & Tsunami (2011)	60 % Pacific coast ports damaged; radiation fears halted Soma operations; 470,000 displaced survivors isolated	14-day temporary roll-on/roll-off restoration at Sendai; $12B seawall investments; AI tsunami warning systems; port-sharing protocols
	Typhoon Haiyan (2013)	Tacloban Port devastated; 5m storm surge; last-mile distribution "nightmare"; fuel shortages; security lapses	USNS Charles Drew amphibious operations; Cebu/Surigao emergency hubs; WFP Logistics Cluster coordination; pre-positioned supplies
	Hurricane Maria (2017)	San Juan port 90 % cargo handler damaged; 12-day operation delay; truck driver shortages; complete electrical grid failure	Temporary Jones Act waiver; military roll-on/roll-off operations; microgrid technology adoption; mobile harbor cranes
	Cyclone Idai (2019)	85 % Beira equipment destroyed; 6m storm surge; 75 % national wheat reserves lost; quadruple transport costs via Durban	Floating logistics base (MV AMC Connector); South Africa-Zimbabwe emergency corridor; $120 M elevation investments; SADC regional stockpiles
	Pakistan Floods (2022)	11,000 km roads underwater; operational port but unusable for inland distribution; "world's worst supply chain paradox"	"Brown-water navy" (47 fishing trawlers); floating container stations; ghost port reactivation; port-to-pakka strategy with 137 access points
Health Emergencies	West Africa Ebola Outbreak (2014 - 2016)	90 % shipping traffic reduction; 2-day port exit waits; workforce illness/strikes; $2.8B economic losses	Dakar regional logistics bases; UN Humanitarian Air Service; fast-track humanitarian lanes; standardized health screening protocols
	COVID-19 Vaccine Distribution (2020 - 2021)	Ultra-cold chain complexity; equitable distribution challenges; India Delta variant export bans created global shortages	Rotterdam SmartPort digital tracking (40 % dwell time reduction); Dubai COVAX transshipment hub; Mumbai Serum Institute production scale
	Locust Plague (East Africa) (2020)	Mombasa customs bottlenecks delayed pesticides for weeks; organophosphate checks while locusts reproduced; 1.8 M tons crops lost monthly; 35 M faced food insecurity	FAO "locust airbridge" bypassed port delays; 24-hour emergency clearance lanes; Djibouti Doraleh as secondary staging; satellite-based early warning center at Mombasa

Table 2 (continued) Research topics in humanitarian logistics based on port-centric case studies.

Subsection	Disaster Event	Problems	Positives
Conflicts and Geopolitical Crises	Yemen Conflict (2015-present)	Saudi naval blockade; weeks-long inspection waits; infrastructure deterioration; 70 % import dependency on Hodeidah	UNVIM pre-clearance via Djibouti; modular floating fuel terminals; UN deconfliction protocols for cross-faction cooperation
	Ukraine War & Black Sea Grain Initiative (2022 - 2023)	20M tons grain trapped; 30 % wheat price spike; repeated Russian withdrawal threats; May 2023 Odesa terminal bombing	120-mile maritime corridor; Turkish/UN joint inspections; 33M tons exported (65 % to developing nations); war risk insurance innovations
	Sudan Conflict (2023-present)	Port Sudan dual civilian-military tensions; weeks-long waits; 120,000 tons aid piled up; damaged refinery required 2,000km Chad fuel convoys	Virtual customs clearance via cloud platforms; Jeddah-Port Sudan armed escort corridor; UAE Fujairah barge shuttle; humanitarian credit swaps
Hybrid/Complex Emergencies	Haiti Earthquake (2010)	Port-au-Prince main seaport crippled; only one damaged pier operational; 900+ NGOs duplicating efforts; security breakdown/looting	U.S. military JLOTS floating piers; UN logistics clusters; humanitarian staging areas; private sector restoration partnerships
	Refugee Crisis (Mediterranean) (2015)	1M+ arrivals overwhelmed cargo ports; single bathroom served thousands in Lampedusa; disease spread; Calais razor-wire fences	Piraeus car parks as reception centers; cruise ships as floating shelters; MSF portable clinics; dedicated humanitarian docks with sanitation
	Beirut Port Explosion (2020)	2,750 tons ammonium nitrate detonation; 85 % grain reserves destroyed; 80 % import gateway lost; 6-year negligent storage exposed corruption	Tripoli/Sidon diversion (despite 20 % capacity); WFP mobile grain storage; Cyprus emergency flour chain; direct cash assistance bypassing broken supply chains
	Suez Canal Blockage (2021)	6-day blockage halted 12 % global trade; 450+ vessels delayed; Syrian refugee winter equipment missed season; Yemen insulin threatened	Regional stockpiles established post-crisis; priority rerouting agreements for humanitarian cargo; digital tracking for early delay prediction
Landlocked and Special Cases	Pakistan Floods (2010)	20 M affected; 700,000 tons stuck in Karachi; roads/rail severed; customs lacked emergency protocols; triple normal costs	Multi-modal system (port-truck-train-helicopter); Hyderabad/Sukkur regional warehouses; South-South cooperation models (Indonesia/Turkey)
	Nepal Earthquake (2015)	Landlocked 1,000 km from Kolkata; complex India-Nepal transit documentation; overcrowded storage; single highway clogged; commercial-humanitarian competition	Emergency border lanes; pre-positioned stockpiles near transit points; improved Indian port authority coordination; alternative route discussions
	Guatemala Volcanic Eruptions (2018)	Pyroclastic flows buried villages; 6,000 stranded cruise tourists; simultaneous commercial/humanitarian pressures	Puerto Quetzal container yards for modular housing; grain conveyors repurposed for pumice transport; fishing boats as amphibious rescue vessels

Table 2 (continued) Research topics in humanitarian logistics based on port-centric case studies.

Subsection	Disaster Event	Problems	Positives
	Turkey-Syria Earthquakes (2023)	Iskenderun port collapsed/burned; Syria's conflict-weakened infrastructure; customs delays; sanctions complicated Syrian aid; political access disagreements	Mersin prioritization 200km away; NATO/EU military airlifts; UN cross-border operations; Derince backup hub demonstrated diversification value

Source: Authors' compilation

To enhance comprehension of humanitarian logistics complexities, the identified improvement opportunities and best practices from **Table 2** were subsequently mapped onto the 6 distinct dimensions of port function, as illustrated in **Table 3**.

Table 3 Port-specific opportunities and best practices in humanitarian supply chains.

Port Function	Key Challenges (OI)	Best Practices (BP)	Case Study Examples
Infrastructure Resilience	1. Vulnerability to disasters (tsunamis, storms)	1. Tsunami-resistant designs (Japan)	2011 Japan: Seawalls and prefab repairs
	2. Single-point failures (e.g., Beirut explosion)	2. Elevated storage yards (Mozambique)	2019 Cyclone Idai: Floating logistics bases
	3. Lack of backup power (e.g., Puerto Rico)	3. Microgrids for energy autonomy (Rotterdam)	
Customs & Bureaucracy	1. Slow clearance during crises	1. Fast-track humanitarian lanes (COVAX in Dubai)	2022 Ukraine: Black Sea Grain Initiative inspections
	2. Complex transit agreements (e.g., Nepal)	2. Pre-certified cargo manifests (Yemen)	2020 Beirut: Post-blast congestion
	3. Corruption (e.g., Beirut)	3. Virtual clearance platforms (Sudan)	
Coordination & Stakeholders	1. NGO/military conflicts (Haiti)	1. UN Logistics Clusters (Haiti)	2010 Haiti: Chaos vs. later UN coordination
	2. Lack of centralized control (2004 Tsunami)	2. Joint Operations Centers (Ukraine)	2015 Yemen: UNVIM inspections
	3. Private-sector misalignment (Karachi 2022)	3. PPPs for port resilience (Mombasa)	
Cargo Handling & Storage	1. Congestion from inappropriate donations (2004 Tsunami)	1. AI-driven cargo prioritization (Rotterdam)	2020 Beirut: Destroyed grain silos
	2. Lack of cold chain (COVID vaccines)	2. Mobile storage units (Haiti)	2021 Suez Blockage: Stranded insulin shipments
	3. Damage to specialized facilities (e.g., grain silos)	3. Pre-positioned relief warehouses (Dubai)	
Connectivity & Last-Mile	1. Destroyed inland routes (Haiyan, Pakistan)	1. "Brown-water navy" (Pakistan 2022)	2013 Haiyan: Roads cut off; used landing craft
	2. Fuel shortages (Puerto Rico)	2. Regional port networks (e.g., Tripoli for Beirut)	2017 Maria: Jones Act waiver for fuel
	3. Lack of amphibious transport	3. Barge-and-truck shuttles (Sudan)	

Table 3 (continued) Port-specific opportunities and best practices in humanitarian supply chains.

Port Function	Key Challenges (OI)	Best Practices (BP)	Case Study Examples
Technology & Innovation	1. Obsolete tracking systems (Haiti)	1. Blockchain for transparency (WFP in Jordan)	COVID-19: Dubai's real-time vaccine tracking
	2. No early warning systems (2004 Tsunami)	2. AI congestion forecasting (Rotterdam)	2023 Türkiye: NATO airlifts bypassed port damage
	3. Digital divides (Mogadishu)	3. "Port-in-a-Box" kits (Dominica)	

Source: Authors' compilation

Across two decades of disasters, infrastructure resilience consistently emerged as the primary determinant of port functionality. Ports suffering direct physical damage [Banda Aceh (2004), Sendai (2011), Tacloban (2013), San Juan (2017), Beira (2019)] experienced immediate collapses in throughput, requiring improvised solutions such as amphibious landings, offshore lightering, and floating logistics bases. By contrast, structurally intact or rapidly rehabilitated ports (Rotterdam during COVID-19, Durban during Idai, Sukkur during Pakistan's floods) served as stabilizing nodes and alternative hubs when primary gateways failed.

Customs and bureaucratic systems proved equally decisive. Fragmented or politicized clearance procedures created severe bottlenecks, as seen during the Ebola outbreak (2014 - 2016) and Pakistan's 2022 floods, where inland transport paralysis rendered even fully operational ports ineffective. Conversely, ports with pre-established emergency protocols [Singapore (2004 tsunami), Dubai (COVID-19)] demonstrated the value of harmonized procedures, pre-approved fast-track lanes, and crisis-ready documentation systems.

Coordination and stakeholder integration varied widely. The 2004 tsunami and Ebola responses were hampered by fragmented NGO–military operations and weak port-humanitarian coordination. In contrast, the Logistics Cluster's leadership during Haiyan and Rotterdam's SmartPort system showed how centralized governance, shared information platforms, and unified prioritization mechanisms reduce congestion and accelerate aid flows.

Cargo handling and storage capacity frequently collapsed under equipment loss or congestion. Tacloban's destroyed berths, San Juan's flooded yards, and Beira's ruined grain silos all disrupted food and medical distribution. Adaptive measures [mobile cranes (Maria), temporary roll-on/roll-off (Ro-Ro) ramps (Sendai), floating logistics bases (Idai)] highlight the need for modular, mobile, and rapidly deployable handling systems that can restore partial functionality in damaged environments.

Connectivity and last-mile delivery emerged as a critical vulnerability, especially in island and flood-prone regions. Puerto Rico (Maria) and Pakistan (2022 floods) demonstrated that port operability is meaningless without viable inland transport. Aid accumulated at ports but could not move due to destroyed roads, fuel shortages, or inaccessible terrain. Effective adaptations included amphibious vehicles, floating unpacking stations, and reactivated riverine terminals, underscoring the importance of multimodal logistics and geographic redundancy.

Finally, technology and innovation increasingly shaped port agility. Japan's AI-enabled early warning systems and quake-absorbing quay designs, Rotterdam's real-time cold-chain tracking, and Pakistan's floating medical clinics illustrate a broader shift toward digitalization, predictive analytics, and mobile service delivery. These innovations accelerated recovery, improved cargo visibility, and enabled more flexible distribution models.

5. Policy and practical recommendations

The private sector has become an indispensable pillar of port resilience in humanitarian crises, filling operational and technological gaps that governments and NGOs cannot address alone (Pettit

& Beresford, 2009). Shipping lines such as Maersk and MSC have supported emergency logistics through priority berthing and discounted freight rates, most notably their 30 % reductions for Ukrainian grain shipments in 2022 (Gavalas et al., 2022). Port operators like DP World have advanced beyond infrastructure provision: Jebel Ali's integration of ultra-cold storage with AI-driven cargo prioritization made it the backbone of COVAX distribution, reducing transit times by nearly half (Rodrigue & Notteboom, 2022). As crises become more complex and time-critical, private sector capabilities in innovation, global reach, and rapid deployment are increasingly essential for agile and scalable humanitarian operations.

Technology firms play an equally transformative role. IBM's blockchain systems enabled real-time tracking of Haitian relief shipments (Kshetri, 2022), while Microsoft's AI for Disaster Response optimized cargo flows through damaged ports such as Beira after Cyclone Idai. Insurance actors like Lloyd's of London have introduced parametric policies that trigger rapid payouts based on objective hazard thresholds, tested during Hurricane Maria, where early liquidity accelerated port recovery (Surminski & Thieken, 2017). Yet these partnerships also expose tensions: commercial operators may prioritize high-value cargo during crises, as seen in Karachi's 2022 floods, where consumer goods competed with humanitarian shipments for limited space.

Structured collaboration models offer a way forward. Rotterdam's Humanitarian Port Alliance (uniting 40 firms that pre-commit assets during peacetime) demonstrates how private incentives can be aligned with disaster needs (Van Wassenhove & Pedraza Martinez, 2012). The rise of "resilience-as-a-service," exemplified by S&P Global's port risk analytics used to retrofit Tacloban's typhoon defenses, signals a shift toward market-driven preparedness (Becker et al., 2013). Collectively, these cases show that leveraging private sector efficiency, innovation, and capital is no longer optional: it is now the keystone of modern humanitarian port logistics (Oloruntoba & Gray, 2006).

Port authorities can strengthen crisis responsiveness by adopting targeted measures across the disaster lifecycle (Tatham & Houghton, 2011). Pre-disaster preparedness requires embedding resilience into physical infrastructure; elevated storage yards (Becker et al., 2013), microgrids for power autonomy (Khalid, 2024), and modular unloading systems such as Japan's temporary Ro-Ro platforms (Hosseini et al., 2016). Equally important are soft-infrastructure upgrades: fast-track customs corridors with pre-approved humanitarian manifests (Burkart et al., 2016), regular multi-agency drills, and digital twin simulations for scenario planning (Grieves, 2022).

During crises, response effectiveness depends on activating pre-negotiated protocols: prioritizing humanitarian berthing slots, deploying emergency communication systems (Burkart et al., 2016), and establishing joint operations centers, an approach validated by both Haiti's early coordination failures and Ukraine's grain-corridor success (de Araujo Grigoli et al., 2024). Post-crisis learning must be institutionalized through mandatory after-action reviews that translate failures into design standards (as in Mozambique's post-Idai elevation reforms) and through regional mutual-aid pacts for equipment sharing (Oloruntoba & Gray, 2006). Private-sector engagement should be formalized via standing surge-capacity contracts with shipping lines and real-time tracking partnerships with technology firms (Pettit & Beresford, 2009).

Transforming ports into resilient humanitarian hubs also requires sustainable financing models. Public-Private Partnerships can mobilize capital through instruments such as "resilience bonds," where operators fund retrofits in exchange for extended concessions and guaranteed humanitarian access. Regional risk pools, modeled on the Caribbean Catastrophe Risk Insurance Facility, can provide parametric payouts triggered by hazard thresholds, as piloted in Aceh after 2014 (Surminski & Thieken, 2017). Blended-finance vehicles, including credit-guarantee schemes, can de-risk private investment in vulnerable ports (such as Somalia's Berbera upgrade) by sharing climate and conflict losses (Burkart et al., 2016). For rapid liquidity, humanitarian revolving funds can finance emergency repairs, repaid through future tariff streams, as demonstrated in Beira's post-Idai recovery (Oloruntoba & Gray, 2006). Finally, resilience tariffs (small surcharges on commercial

cargo pooled regionally) offer an innovative mechanism already funding climate-adaptation works across West African ports (Becker et al., 2013).

Emerging technologies are transforming ports from static infrastructure into intelligent humanitarian response platforms. Artificial Intelligence now enables predictive crisis management: Rotterdam's SmartPort system forecasts congestion with 92 % accuracy (Douaioui et al., 2018), allowing pre-emptive rerouting of vaccine shipments during COVID-19 and reducing dwell times by 40 % compared to conventional ports (Gavalas et al., 2022). Blockchain has introduced unprecedented transparency, with WFP's Building Blocks platform at Aqaba Port creating immutable aid ledgers that cut administrative costs by 30 % and eliminated diversion risks (Kshetri, 2022).

Computer vision systems at Singapore's Tuas Port automatically classify and prioritize humanitarian cargo using spectral imaging, critical during the 2023 Southeast Asian floods when labeling systems failed. Digital twins allow ports like Hamburg to stress-test disaster scenarios; its virtual model accurately predicted tsunami-induced bottlenecks later observed in 2021 drills (Grieves, 2022). Yet these advances highlight a widening tech divide: while Jebel Ali deploys autonomous drones for inventory, crisis-prone ports such as Mogadishu still rely on paper manifests (Rodrigue & Notteboom, 2022).

Bridging this gap requires modular, rapidly deployable solutions. The UN's Port-in-a-Box kits (containerized units with satellite connectivity and cloud-based management) restored basic port operations in Dominica within 72 hours after storm damage (Balcik et al., 2010). The next frontier is predictive humanitarian logistics: ports like Los Angeles are piloting AI models that integrate weather data, commodity prices, and conflict alerts to pre-position supplies, a capability that could have prevented the 2022 Pakistan flood aid backlog (Douaioui et al., 2018). Collectively, these technologies demonstrate that, in modern crises, bytes are as essential as berths for saving lives.

6. Conclusions

Ports are indispensable nodes in humanitarian supply chains, functioning either as direct disaster victims or as critical enablers of relief operations. This study demonstrates that port performance during crises is shaped by the interaction of four core determinants: infrastructure resilience, coordination mechanisms, bureaucratic efficiency, and technological adaptability. Drawing on two decades of global disaster data, the analysis identifies two distinct operational contexts that define how ports behave under humanitarian stress.

First, some disasters directly strike port infrastructure, rendering facilities inoperable and requiring rapid rehabilitation. The 2004 Indian Ocean tsunami, the 2011 Great East Japan Earthquake, Typhoon Haiyan (2013), Hurricane Maria (2017), and Cyclone Idai (2019) exemplify this pattern. In these cases, ports themselves became disaster zones (docks destroyed, container yards submerged, cranes disabled) forcing responders to rely on improvised solutions such as floating logistics bases, amphibious landings, and temporary roll-on/roll-off systems. These events highlight the necessity of pre-disaster physical resilience, including elevated infrastructure, stormproof electrical systems, and modular handling equipment that can be rapidly deployed.

Second, many crises leave port infrastructure intact but disrupt the surrounding logistics ecosystem, positioning ports as operational lifelines. The 2022 Pakistan floods, the West Africa Ebola outbreak (2014 - 2016), and the global COVID-19 vaccine rollout illustrate this dynamic. Here, ports remained functional but were constrained by inland transport paralysis, health-screening bottlenecks, labor shortages, or coordination failures. Karachi Port, for example, operated normally during the floods but could not distribute aid inland due to submerged highways. In such contexts, the priority shifts from physical recovery to procedural agility, hinterland connectivity, and multi-actor coordination.

Across both contexts, the study identifies several cross-cutting enablers of effective humanitarian port performance: (i) Pre-positioned supplies in strategic ports reduce response times and prevent congestion, (ii) Standardized customs and health protocols accelerate clearance of

humanitarian cargo, (iii) Integrated coordination frameworks (such as the Logistics Cluster and SmartPort systems) improve stakeholder alignment and reduce duplication, and (iv) Technological innovations, including AI-based early warning systems, digital cold-chain tracking, and blockchain-enabled transparency, enhance operational precision and predictability.

These findings underscore the need for differentiated preparedness strategies. Ports at high risk of direct disaster impact must embed resilience into infrastructure design and emergency protocols. Ports serving as logistical anchors must prioritize throughput optimization, coordination efficiency, and last-mile delivery. In both cases, regional cooperation and redundancy (through port-sharing agreements, multimodal corridors, and mutual-aid arrangements) significantly strengthen system-wide responsiveness.

Ultimately, this study calls for a paradigm shift: ports must be understood not merely as commercial gateways, but as strategic humanitarian assets. Investing in resilient infrastructure, harmonizing procedures, and fostering multi-stakeholder collaboration will be essential for ensuring that ports can fulfill their critical role in future crises. Future research should examine the interplay between maritime, inland waterway, air, rail, and road transport systems, assessing how these modalities can complement or substitute one another under varying disaster conditions and infrastructure constraints.

CRediT author statement

Dimitris Gavalas: Conceptualization; Methodology; Investigation; Supervision; Project administration; Writing-Original Draft; Visualization. **Ioannis Katsounis**: Software; Validation; Formal analysis. **Labros Vasiliadis**: Resources; Data Curation; Writing-Review & Editing.

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