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Evaluation of global health, disaster response, and humanitarian projects and programs

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Health effects of radioactive contaminated dust in the aftermath of potential nuclear accident in Ukraine

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One-sentence summary

Our simulation shows widespread radioactive contamination in the event of nuclear accident(s) during the Ukraine war, but the extent and direction of the impact will depend on the timing of the accident.

Introduction

Thirty-six years have passed since the largest uncontrolled radioactive release at the Chernobyl nuclear power plant in Ukraine. Large amounts of iodine (I) and cesium (Cs) radioisotopes were scattered over a wide area. The total radioactive dose from Chernobyl is estimated at 80,000 man-sieverts, and the death toll was more than 200,000 (1). The current Ukraine war raises serious intentional or unintentional risk of another nuclear disaster. Thus, this research examines the spatiotemporal distribution of potential radioactive dust in the event of accidents in power plants in Ukraine. Here, we modeled air mass movements over the region using the HYSPLIT model and archived meteorological data from April 2021 to March 2022 under the assumption of explosion and release of radioactive particles after referring to as "incident" in any or all Ukrainian nuclear power plants at the same time. Furthermore, we used model outputs to study which countries are likely to be affected by the radioactive dust 3 days after the incident.

FIGURE 1
Locations of the Ukrainian nuclear power plants. Base map is from Google Earth.

TABLE 1 Name, capacity, and coordinates of the Ukrainian nuclear power plants.

Name	Capacity (MW)	Latitude	Longitude
Khmelnytska	2,000	50.3024	26.6473
Rivne (Rouno)	2,835	51.3245	25.8974
South Ukraine	3,000	47.812	31.22
Zaporozhye	6,000	47.5119	34.5863

The health effects of radioactive dust exposure are also discussed based on data collected after the Chernobyl incident.

Materials and methods

Site locations

Ukraine has four operational nuclear power plants with a capacity ranging from 2,000 to 6,000 megawatts and located in the northwest and south of the country [Figure 1 and Table 1 from Global Power Plant Database (2)]. The Rivne (Rouno) and Khmelnytska power plants are located in the northwest almost at the same longitude but 130 km apart, while the South Ukraine and Zaporozhye power plants are located at the same latitude but 255 km away from each other.

HYSPLIT forward-trajectory climate simulations

Three-days air mass forward trajectory ensemble plots at 500 m starting altitudes were computed for the first week of each month from April 2021 to March 2022 using the online web version of the HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) model (3, 4). HYSPLIT is one of the most extensively used atmospheric transport and dispersion models on earth by the atmospheric sciences community, which has evolved for more than 30 years. Its calculation method is a hybrid between the Lagrangian approach and the Eulerian methodology. HYSPLIT proved to be a complete system for computing not only a simple air parcel trajectory but also complex transport, dispersion, and deposition simulations, and it was successfully used to model the fallout from nuclear clouds (5).

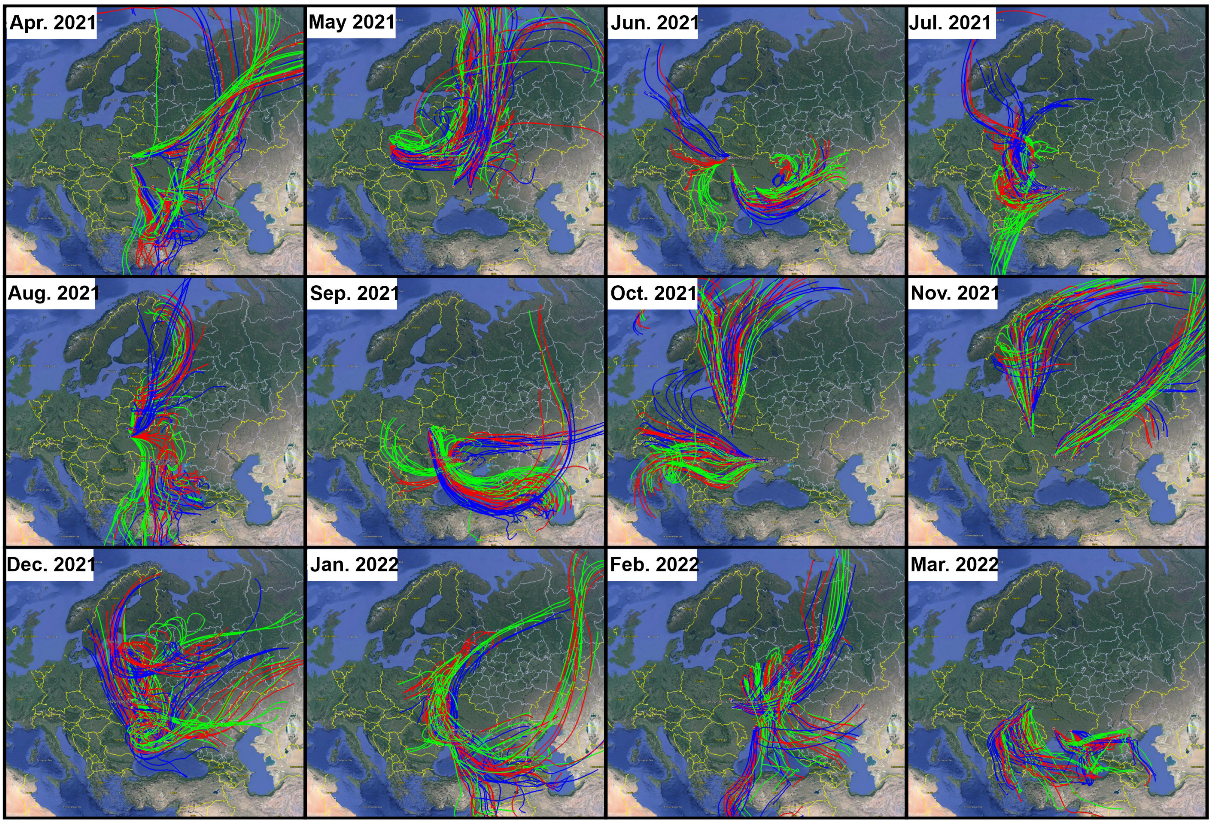

FIGURE 2
Three-day forward trajectory for the studied sites for the first week of each month starting from April 2021 to March 2022. Base map is from Google Earth.

Similarity between trajectories for different timeframes was tested for one of the cites (Rivne) for the first week of each month from April 2020 to March 2021 and from April 2021 to March 2022. The dispersion pattern and movement of air parcel originated from the Rivne site during the aforementioned time frames shows similar pattern (Supplementary Figure S1). Therefore, the time window of April 2021-March 2022 was chosen to represent the atmospheric circulation during the recent 12 months. The starting altitude range for the HYSPLIT model was chosen to be 500–2,000 m to provide maximum coverage for aerosol-bearing air masses that pass over the study area. To incorporate diverse instrumental data into a gridded, 3-D model space, the Global Data Assimilation System with one degree resolution (GDAS1) (https://ready.arl.noaa.gov/archives.php) was used to provide a comprehensive meteorological dataset for the HYSPLIT model. The coordinates of each nuclear power plant were used as the emission source of air masses.

Result and discussion

Results of the HYSPLIT three-days air mass forward-trajectory originated from the locations of the nuclear power plants in Ukraine are shown in Figure 2. As illustrated in Figure 2, the patterns of the air mass movement over the region show a large spatial and temporal variability. This suggests that the radioactive dust generated from the point sources will affect Ukraine, west of Russia, and other countries depending on the timing of the incident during the year (or season). Table 2 summarizes the countries that will be impacted by contaminated air masses during different months of the year. The HYSPLIT trajectories suggest that during the winter months 3 days after the occurrence of an incident in Ukrainian nuclear power plants, countries in central, south, and southeastern Europe as well as countries in the Middle East may receive radioactive-contaminated aerosol. During the fall, the air parcels containing radioactive-contaminated aerosols may hover over the countries in central, north, south, and southeastern Europe.

TABLE 2 List of countries which contaminated air mass will potentially travel over their air space from April 2021 to March 2022.

Month	Potentially affected countries
April 2021	Russia, Belarus, Moldova, Romania, Turkey, Cyprus
May 2021	Russia, Belarus, Poland, Lithuania, Latvia, Estonia, Finland
June 2021	Russia, Belarus, Poland, Denmark, Sweden, Norway, Germany, Slovakia, Romania, Moldova, Hungary, Serbia, Kosovo, Macedonia, Greece
July 2021	Russia, Belarus, Poland, Denmark, Sweden, Norway, Germany, Slovakia, Romania, Moldova, Hungary, Serbia, Macedonia, Greece, Libya
August 2021	Russia, Belarus, Lithuania, Latvia, Moldova, Finland, Turkey, Greece
September 2021	Russia, Moldova, Romania, Slovakia, Hungary, Serbia, Czech Republic, Poland, Georgia, Azerbaijan, Kazakhstan, Iran, Turkmenistan
October 2021	Belarus, Lithuania, Latvia, Estonia, Finland, Sweden, Norway, Slovakia, Romania, Serbia, Czech Republic, Germany, Italy, Austria, Switzerland, Croatia, Bosnia and Herzegovina
November 2021	Russia, Belarus, Lithuania, Latvia, Estonia, Finland, Sweden
December 2021	Russia, Belarus, Lithuania, Latvia, Estonia, Poland, Finland, Sweden, Moldova, Romania, Poland, Kazakhstan
January 2022	Russia, Belarus, Lithuania, Latvia, Georgia, Azerbaijan, Turkmenistan, Uzbekistan, Kazakhstan, Turkey, Syria, Iraq, Iran, Lebanon
February 2022	Russia, Belarus, Kazakhstan, Georgia, Turkey, Israel, Syria, Iraq, Lebanon, Jordan
March 2022	Russia, Moldova, Romania, Hungary, Serbia, Kosovo, Macedonia, Bulgaria, Turkey, Greece

In summer months, air parcels with radioactive-contaminated aerosols may travel over countries in central, north, south, and southeastern Europe, part of the Middle East, north Asia, and even North Africa. Finally, countries in central, north, south, and southeastern Europe may receive contaminated air parcels if the incident happens in Ukrainian nuclear power plants during spring. Major water bodies that could be affected by contaminated air parcels are the Black Sea, Baltic Sea, Mediterranean Sea, and, to a lesser extent, Caspian Sea. The contaminated dust would not reach the United States, at least after the first few days of the potential incident.

The health effects of radioactive dust may be classified as early and late health effects. Acute radiation syndrome (ARS) may occur in the 30 km^2 around each burst plant resulting in death mainly due to significant skin injuries and bone marrow failure. People who survive from ARS may suffer from cataract, skin injuries, respiratory illnesses such as emphysema and bronchitis, and sexual dysfunction (6–8). Data show that 134 of 600 workers were diagnosed with ARS within hours after the Chernobyl accident. The sickness was seen among the power plant employees and first responders but not in the evacuated population or the general population. Nearly all people with a whole-body dose of more than 6.5 gray (Gy) died within 3 months (9).

Late health effects mainly occur because of development of malignant lesions. A marked increase in thyroid cancer incidence was reported in Belarus, Ukraine, and the four most contaminated regions of Russia (Bryansk, Kaluga, Orel, Tula); among those were younger than 18 years at the time of the Chernobyl nuclear accident. The total number of cases of thyroid cancer due the Chernobyl accident registered between 1991 to 2015 among 18 years or younger in Belarus, Ukraine, and the most contaminated regions of Russia exceeded 19,000 (10). Children and adolescents received high radiation doses to the thyroid mainly because of consumption of fresh milk containing ^{131}I, specifically in the 8 weeks following the disaster, and because of iodine's 8-day half-life (11). Individual thyroid doses due to radioactive iodine ingestion fluctuated up to 42 gray (Gy) and depended on the age of the individual, region of exposure, and individual's dairy product consumption habits. Population-average thyroid doses among children of youngest age reached up to 0.75 Gy in Belarus most contaminated area, the Gomel Oblast (12–15).

A Chernobyl cohort of registered recovery and cleanup workers who received radioactive doses varying from 20 to 500 mSv and were followed up over the period 1992–2009 showed a significant increase of 18% in all solid cancers. Furthermore, the dose-response relationship was confirmed (16). In contrast to the substantial increase in thyroid cancer incidence among those exposed at under 18 y, except in clean-up workers, no meaningful evidence of any statistical association between radionuclide exposure and leukemia risk yet exists. Previous studies couldn't establish a consistent correlation between radiation and leukemia incidences in the exposed populations (9, 17, 18).

Nonmalignant diseases may develop in victims of remote exposure to radionuclide dust particles. Since the release of the WHO 2006 report, there has been emerging evidence that radiation as low as 20 mSv can lead to radiation-induced cataracts (19–21) and potential cardiovascular disease (22, 23).

According to experts, psychosocial impacts are the disaster's main public health issues that have affected the largest number of people. Common problems include cerebrovascular diseases, organic mental and mood disorders, and cognitive impairments such as dementia that increased with irradiation dose exposure. Interestingly, radiation exposure level was found to be a common risk factor for mental health effects of the Chernobyl, Fukushima, and 3-mile island nuclear disasters (9, 24, 25).

The current trajectory models are based on the archived data and only present the movement of air masses for the first week of each month. To better understand the movement of air masses that could originate from the Ukrainian power plants and the possibility of countries receiving contaminated air parcels, we recommend a weekly trajectory frequency for each month of the year to be utilized.

Author contributions

Conceptualization: AS and MM. Methodology and visualization: AS. Investigation and writing-original draft: AS, RD, and MM. Supervision: MM. Writing-review and editing: AS, RD, NK, and MM. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpubh.2022.959668/full#supplementary-material

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Health and nutrition emergency response among internally displaced persons at Ranch collective site, Chagni, Ethiopia: The role of emergency operation center, lessons from the field, and way forwards

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Background: In October 2020, about 79,041 ethnically Amhara/Agew people had been internally displaced (IDPs) from Metekel zone of Benishangul-Gumuz region and lived in Ranch collective site, Chagni town, Ethiopia. Onsite PHEOC met the health and nutrition needs of the IDPs as per international humanitarian response standards.

Methods: On January 11/2021, the Amhara Public Health Institute (APHI) established an onsite Public Health Emergency Operation Center (PHEOC) at Ranch collective site. Health workers and vehicles were deployed. A temporary clinic having nine outlets was built. Drugs and medical supplies were mobilized from different sources. The overall response period lasted about 8 months, from December 2020 up to June 2021.

Results: A total of 33,410 IDPs had received free essential health services. Mental health and psychosocial support services had been given for 1,803 cases. Specialized medical services such as trachomatous trichiasis (30), cataract surgery (8) and sputum samples for mycobacterium tuberculosis (120) have been done. Moreover, 454 women received antenatal care services and 137 women gave birth at health facilities. About 837 children have got measles supplementary dose and 1,280 adults took a COVID-19 vaccination. A total of 1,448 children under five, 454 pregnant and 402 lactating women had been screened on monthly basis. Of which, severe and moderate malnutrition rate was 46 (3.2%) and 75 (5.2%), respectively. A total of 194 trench latrine seats, 74 shower rooms and 50 hand washing facilities had been constructed. There were no human feces present nor solid wastes accumulated around the shelters or settlements. Both active and passive surveillance activities were carried out throughout the camp life. We also conducted regularly Risk Communication and Community Engagement activities on priority health issues.

Conclusion: We adequately met the health and nutrition needs of the IDPs as stated in the Sphere humanitarian handbook. We sought to have a strong Incident Management System and coordination platforms like PHEOC, a resilient health system, a training curriculum called Leading in Emergencies, and a multipurpose collective center with infrastructures, humanitarian response guidelines, training materials, and risk/vulnerability-based preparedness plan.

KEYWORDS

emergency response, IDPs, health, nutrition, PHEOC, Ranch collective site

Background

In recent years, the Amhara people living within and outside the region are being displaced due to politically provoked ethnic-based attacks. On December 14/2021, the Amhara Public Health Institute and the Regional Disaster Prevention and Food Security Commission reported that over 2,356,587 ethnically Amhara individuals had been intentionally uprooted from their indigenous residency in different regions and lived in 37 collective sites and the host communities (1). The cause of displacement was ethnic-based attacks against civilians, armed conflict, and escalating tensions in Benishangul-Gumuz and Oromia regions, and because of the war with Tigrayans Invading Forces in the northern part of the country.

Between October 2020 and June 25/2021, a total of 79,041 ethnically Amhara/Agew individuals had been displaced from Metekel zone of Benishangul Gumuz region because of ethnic-based attacks and lived in Ranch collective site, Chagni town. To facilitate emergency humanitarian responses, the Amhara regional government established Emergency Coordination Center (ECC) in Chagni. Following this, the Amhara Public Health Institute prepared a health and nutrition emergency response plan and activated an onsite Public Health Emergency Operation Center (PHEOC) in Chagni town on January 11/2021. Thus, the overall health and nutrition emergency responses in Ranch/Chagni collective site were delivered through an onsite PHEOC team in collaboration with the ECC and other humanitarian actors.

In developing countries like Ethiopia, the health needs of IDPs are not well-known and are poorly met in these countries (2). To overcome these, we established an onsite PHEOC to ensure that the health and nutrition needs of the IDPs are met and delivered according to international humanitarian response standards like Sphere Handbook, with a coordinated effort.

Despite the large numbers of IDPs/refugees in different countries, documented experiences about health service delivery approaches and methodologies in the camp are limited and previous studies are narrowed on the health needs of the IDPs, or a single disease/service and the accessibility of the services, but the way how we deliver humanitarian services is forgotten. In this paper, we have tried to report a more comprehensive picture of humanitarian operations in the Ranch camp with a more emphasis on the process and service delivery approaches to fill the above literature gap.

Emergency response methodology

Response design and period

On January 01/2021, the Amhara Public Health Institute activated the regional offsite Public Health Emergency Operation Center (PHEOC) in Bahir Dar city. Similarly, on January 08/2021, the regional government established Emergency Coordination Center (ECC) in Chagni town. Following this, the institute also established an onsite PHEOC in Chagni town on January 11/2021. Humanitarian responses were officially started in November 2020 and ended on June 25/2021 after 8 months of operations. Cessation of health service delivery was carried out once the IDPs were fully returned to their place of origin.

Onsite PHEOC/IMS organogram

The Incident Management Structure (IMS) for Ranch EOC was adapted from the World Health Organization handbook for developing a PHEOC (3). As shown in Figure 1 below, the onsite PHEOC has its incident commander, deputy incident commander and operation section chief and unit members. The onsite PHEOC is directly accountable to the ECC in Chagni

Abbreviations: APHI, Amhara Public Health Institute; ECC, Emergency Coordination Center; EOC, Emergency Operation Center; GBV, Gender-Based Violence; MHPSS, Mental Health and Psychosocial Support; HCWs, Health Care Workers; IDPs, Internally Displaced Peoples; IMS, Incident Management Structure; PHEOC, Public Health Emergency Operation Center; RCCE, Risk communication and community engagement; WaSH, Water, Sanitation and Hygiene.

town and reports to the offsite PHEOC in Bahir Dar city. Besides, the onsite PHEOC had a direct line of communication with the Awi Zonal Health Department, Chagni Town Health Office, and other humanitarian actors.

Human resources recruitment and staffing

A total of 18 healthcare workers (HCWs), 4 drivers and 92 volunteer IDPs were staffed in the IMS structure. We mobilized the PHEOC team from Amhara Public Health Institute (3), Awi Zonal Health Department (1), Chagni Town Health Office (1), Chagni Primary Hospital (4), Chagni Health Center (1), MSF Spain (8), non-employed volunteer HCWs (4) and volunteers IDPs (92). Volunteers were selected together with tent leaders using flexible criteria like having a grade 10 level of education, being a 24-h tent-resident, being among the displaced community, good communication skills with Amharic and Agewugna languages, and from each sex, tent, or kebele/district of displacement. Also, efforts had been made to recruit dedicated, passionate, and multi-disciplinary HCWs and drivers. All of these were staffed in the IMS organogram of Ranch collective site as *full-time workers* (Figure 1).

Despite this, there was no mobile health and nutrition team deployed in the camp. However, a different surge team was deployed for a short period in an *ad-hoc* manner. The first was a team of 7 mental health and psychosocial support (MHPSS) professionals deployed by the Ethiopian Public Health Institute for 21 days. The second was a team of 5 general practitioners deployed by Amhara Emergency Fund for 12 days, and the third was a team of 20 multi-disciplinary medical experts deployed by Fewus Charity Association for 5 days and the last was a team of 24 MHPSS experts deployed for 20 days by the Amhara Public Health Institute in collaboration with Injibara University and Awi Zonal Health Department.

Site selection, setting and population

Initially, the IDPs resided in an open-field self-settlement site called "Ranch," which is part of Chagni town, Amhara region. They were shaded in an extremely large tree called *Sycamore*, meaning "*Warka*" in Amharic (Figure 2). Then after, in the first week of January, ECC team was deployed in Chagni town. Immediately, the team had made a discussion with Chagni town and Gangua district administrative bodies about the humanitarian response and jointly selected an appropriate settlement site called "Ranch collective site or IDPs site," which is located nearly 4 kilometers from Chagni town (Figure 2). Also, it is 506 Km far from Addis Ababa, the capital city of Ethiopia in the northwest direction and 177 km from Bahir Dar, the capital city of Amhara regional state.

Out of 79,041 IDPs, 31,868 (40.3%) of them had lived in the camp and the rest 47,173 IDPs were living in the host community while collecting their humanitarian aids like food and non-food items, and free medical services from Ranch IDPs site. They were displaced from seven districts of Metekel zone of Benishangul-Gumuz region: namely, Dangur, Dibatie, Mandura, Bullen, Guba, Gilgel Beles and Wombera. But the majority were from Dangur (40.6%) and Dibatie (21.8%) districts. In the camp, there was a registry of 1,448 children under five, 141 pregnant and 402 lactating women. An additional 313 pregnant women who were living in the host community had received essential health services from the camp. There was also a non-registered/uncounted number of children under five who were living in the host community while receiving health services from the camp.

Partners involved in health and nutrition emergency response

Four non-governmental organizations had been engaged in health and nutrition emergency response at Ranch collective site. The MSF Spain was the leading humanitarian agency acting on hygiene and sanitation issues, risk communication and community engagements (RCCE), provision of drug and medical supplies, and essential health service delivery. Also, UNICEF had been acting on nutrition emergencies, provision of emergency drug kits and financial support. The Catholic Relief Services (CRS) was supplying water for the IDPs and supporting hygiene and sanitation-related activities. Johns Hopkins Center for Communication Programs supported risk communication and community engagement activities focusing on COVID-19 and Gender-Based Violence. All agencies were providing technical support for the PHEOC and ECC teams. They were reporting their daily activities to the PHEOC planning section.

Emergency response monitoring and evaluation

We had prepared a three-month health and nutrition emergency response plan. From this plan, we prepared weekly and daily Incident Action Plans (IAP) throughout our stay. We also evaluated our emergency response status on a daily and weekly basis with the PHEOC and ECC teams. Besides, the offsite PHEOC which is situated in Bahir Dar was closely following the onsite response on a daily and weekly basis with acting partners. Also, we had been conducting weekly cluster meetings with health and nutrition sector humanitarian actors. Throughout the response period, we

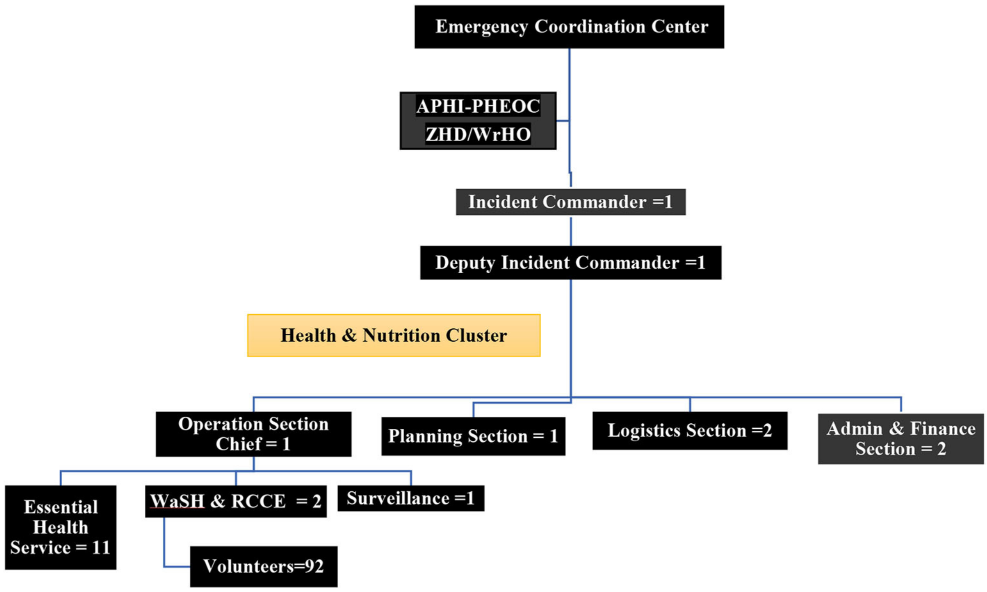

FIGURE 1
Ranch collective site onsite-PHEOC incident management structure/organogram, November 2020 to June 2021, Changi, Ethiopia.

produced and distributed 33 humanitarian response Situation Reports (SitRep). Our means of communication during the response were through a phone call, telegram, Facebook, email and paper-based. Daily onsite work attendance and meeting minutes had been recorded throughout the response period. Finally, an after-action review meeting had been conducted and all contributing agencies and individuals were acknowledged and certified by the Amhara Public Health Institute on July 10/2021 at Debre Tabor town. The success of the onsite PHEOC was evaluated based on the accessibility/availability of 24-h essential health/nutrition services, the ratio and adequacy of WaSH indicators to the displaced persons, the existence of a vibrant surveillance system in the camp, an appropriate risk communication strategy and other national/international humanitarian standards.

Data reporting and information management

Throughout the response period, data were collected daily using a structured data collection and reporting tool. The tool addressed pertinent indicators regarding essential health services, WaSH and RCCE activities, and other health-related services. The primary data sources were clinical service registries, direct observations, the IDPs, daily situation reports, and other records. All humanitarian partners were also reported to the onsite PHEOC planning section on daily basis. Two of the investigators were leading the overall health and nutrition emergency response throughout the camp life. Thus, they were in charge of coordinating the data collection and reporting activities on daily basis as part of their duty for a prompt response. Data quality was assured through daily data cleaning, discussion with the PHEOC teams, training, and supervision. Daily, data entry and analysis had been done using Microsoft Excel 2016. Situation updates had been released regularly for concerned bodies.

Definitions of terms

Internally displaced persons: are individuals who had been forced or obliged to flee from their homes or places of habitual residence due to natural or man-made disasters, and who have not crossed an internationally recognized state border (4, 5).

A public health emergency operation center: is a place within which the preparation, response, and recovery phases of public health emergencies are better coordinated. Sometimes, in the document, we used the term EOC to represent PHEOC (6, 7).

On-site PHEOC: is a tentative PHEOC established by the Amhara Public Health Institute in Chagni town, Ranch IDPs site, that served as a hub for better coordination of health and nutrition emergency response.

The incident management system (IMS): It is an emergency management structure with protocols and procedures that provides an approach for the coordination of response through a PHEOC, primarily to respond to and mitigate the effects of all types of emergencies (6, 7).

FIGURE 2
Ranch self and planned settlement site, Changi, Ethiopia, November 2020 up to June 2021.

Emergency coordination center (ECC): is operationally defined as a multi-sectoral team established by the regional government to carry out all the five functions of the emergency operation center in Chagni town, Ranch IDPs site.

Situation report (SitRep): A routinely produced report that provides current information about health and nutrition emergency response at Ranch IDP site, its major gaps/challenges, and the way forward.

Public health emergency: this means an extraordinary event that constitutes a public health risk through the spread of disease and potentially requires an immediate and coordinated national or international response (3).

Diagnosis of cases: Malaria, diabetes mellitus and pregnancy were diagnosed using a rapid diagnostic test kit, random blood sugar test, and urine test strips, respectively.

Results

Essential health services

Temporary clinic set up

Initially, essential health services had been delivered at Chagni Primary Hospital free of charge. After a month, a "Temporary Clinic" at Ranch collective site was established. Yet, free medical services had been delivered at nearby hospitals through strong referral linkages.

The Ranch temporary clinic was established with five UNICEF-funded tents, having nine service delivery outlets: namely, two adult outpatient departments (OPDs), two under five OPDs, one dispensary, one maternal and child health service room, one mental health and psychosocial support room, waiting and triage rooms (Figure 3). Eleven healthcare workers

(HCWs) were assigned to the temporary clinic; 3 were from Chagni primary hospital, 4 were volunteer health professionals and the rest 4 were MSF Spain staff. MSF Spain also assigned cleaners and guards to the clinic. The APHI allocated an ambulance to patient referral that also provides transportation services for clinicians. Emergency nutrition and mental health services were also integrated with other clinical services in the clinic. MSF Spain offered a myriad of supports like human resources, and the provision of drugs and medical supplies. Simple and rapid laboratory testing options like malaria Rapid Test Kits, pregnancy test strips, Hemoglobin, Random Blood Sugar, and urine dipstick were availed in the temporary clinic.

Essential health services

During the camp life, a total of 33,410 IDPs accessed essential health services from the Ranch temporary clinic and Chagni primary hospital through referral. Among these, 31,832 (95%) were cases with a kind of illness that needs medical interventions, while the rest had come for health promotion and disease prevention services. The average outpatient visit per day was 200 (150–250) cases. Regarding the age of patients, 1,938 (6.1%) were children <1 year, 5,381 (16.9%) aged one up to 4 years, 4,490 (14.1%) in between 5 and 14 years and the rest majority 20,022 (62.9%) were adults of 15 years and above. Mental health and psychosocial support had been given at least for 1,803 cases. Furthermore, specialized medical services like trachomatous trichiasis surgery (for 30 patients), cataract surgery (for 8 patients) and other minor and major surgical services (such as 13 caesarian sections) had been done through an outreach and referral system. In addition, a sputum sample for tuberculosis (TB) was collected from 120 suspected cases and 1 pulmonary TB case was detected and 5 contacts were screened negative. There was a total of 4 adult deaths among the IDPs. The cause of death was car accidents on the road, gun shoots and present chronic illness.

Maternal and child health services

Four hundred fifty-four pregnant women had received Antenatal Care (ANC) services at least once and 137 of them gave birth at health facilities, including 13 cesarean sections. The rest, 317 (69.8%) women, were returned to their original residencies while they were pregnant. Post-natal care services were delivered to 137 women. Ultrasound investigation had been done for 73 pregnant women during their ANC follow-up. Besides, 542 mothers received modern contraceptive methods. Childhood vaccinations had been given on a routine and campaign basis. In general, 137 children received the first dose of oral polio vaccine, 155 children got pentavalent 1st dose, 112 took pentavalent 2nd dose, 92 pentavalent 3rd doses, 74 and 66 children received the first and second dose of measles, respectively. Besides, 837 children under five had got supplementary measles doses through the campaign and 1,280 adults received the first dose of AstraZeneca's COVID-19 vaccine. Also, 91 adolescent girls aged 14 years got the human papillomavirus vaccine through a campaign. We vaccinated all eligible children living in the camp. Most children were fully vaccinated before displacement. That is why the number of vaccinated children in the camp seems low. Yet, few children that were living outside the camp might remain unvaccinated.

Emergency nutrition services

A total of 1,448 children under five had been screened monthly. Of these, 46 (3.2%) were severely malnourished, and 75 (5.2%) were moderately malnourished with a Global Acute Malnutrition rate of 8.3%. Forty-one severely malnourished children (89.1%) were linked to outpatient therapeutic feeding and/or stabilization centers. On the other hand, 141 pregnant and 402 lactating women had been screened regularly and 135 (25%) were found to be moderately malnourished. The rest pregnant women were living in the host community, and we failed to screen them on monthly basis; but MUAC was taken irregularly. For mothers and children who were affected with moderate malnutrition, additional fortified foods had been given monthly. During the camp life, each household had got a general food ration of 15 kilo grams per person per month. An additional food commodity had been given regularly to households with children under-five, pregnant/lactating women and people living with HIV, to prevent acute malnutrition.

Water, hygiene and sanitation (WaSH)

A total of 194 trench latrine seats (100 for females), 74 shower rooms (50 for females) and 50 hand washing facilities were constructed (Figure 4). One hundred forty-four of the latrine seats and all the shower rooms were constructed by MSF Spain, while the rest 50 latrine seats were built by the Catholic Relief Services. All toilets were sited appropriately and adequately distanced from any surface or groundwater source. The estimated distance between dwellings/shelters and shared toilets ranged from 60 to 100 meters. All toilets have internal locks, easy to use and keep clean, but no lighting. Besides, they were not suitable for fly and mosquito breeding, had a minimal smell and had adequate space for different uses, which allows for the dignified cleaning, drying and disposal of women's menstrual. Further, toilets were provided with easy access to water for handwashing, anal cleansing, and flushing.

Two water tracking rotos with a capacity of 10,000 liters were installed for water supplies to latrines and shower rooms. In addition to the shower rooms, there is a naturally occurring body of water, which serves as a recreational area; especially male IDPs were taking a shower in the pond and river while

FIGURE 3
Layout of Ranch temporary clinic, Changi, Ethiopia, November 2020 up to June 2021.

FIGURE 4
Trench latrine seats constructed in Ranch collective site, Changi, Ethiopia, November 2020 up to June 2021 ($N = 194$).

recreating themselves (Figure 5). At least 2 soaps per person per month had been provided for bathing and laundry purpose. Women's dignity materials were also distributed regularly to women of reproductive age groups. Moreover, 19 medium-sized solid waste management pits have been prepared around the settlements. Thus, all tents have access to designated communal solid waste collection points. The WaSH team and the IDPs had conducted regular sanitation campaigns. Also, tent inspection has been conducted routinely by trained IDP volunteers. Generally, there were no human feces present nor solid wastes accumulated around the shelters or settlements. And we judged that the WaSH services in the camp were adequate, appropriate, and acceptable to the IDPs.

Risk communication and community engagement

We established Mini Media with support from Johns Hopkins Center for Communication Programs through its "Communication for Health" program, which serves as a broadcasting center. In addition, we endorsed a tent-to-tent risk communication approach to address residents in each tent. Thus, health information on priority health issues and treats had been effectively delivered routinely. The main areas of risk communications were environmental and personal hygiene, mental health problems, COVID-19, gender-based violence, scabies, tuberculosis, sexually transmitted disease,

FIGURE 5
Shower rooms and swimming pool in Ranch collective site, Changi, Ethiopia, November 2020 up to June 2021 ($N = 194$).

community/event-based surveillance, water and food-borne diseases, malnutrition, malaria and extra. That is how we empowered the IDPs and engaged them in emergency WaSH/IPC implementation, event-based surveillance, essential health service uptake, and other humanitarian operations.

Public health surveillance

In the camp, both indicator and event-based surveillance approaches had been phased for early detection and prompt response to public health threats. Rumors and early warning signals have been verified soon through active surveillance. For instance, one sample from cholera and two samples from measles suspected cases were taken to the regional laboratory and all were tested negative. Standard surveillance tools like data collection and reporting, case definitions and guidelines had been availed and orientation training for the PHEOC team had been given. Data on clinical case management had been collected and analyzed on daily basis and disseminated through situation reports.

Throughout the camp life, a total of 31,832 (95% of the total OPD visits) IDPs had been medically treated with a kind of acute or chronic medical illness (Table 1). The most diagnosed health problems were pneumonia (13.2%), acute febrile illness (11.1%), intestinal parasite (9.5%), acute upper respiratory tract illness (7.7%), none-bloody diarrhea (6.8%), dyspepsia (6.2%) and ophthalmologic problems (5.8%). Scabies and malaria (RDT confirmed) contribute 4.6% and 2.4% of the cases. Epidemiological trends of common epidemic-prone diseases like malaria, scabies and diarrhea were observed closely and found to be constant throughout the response period. There was no occurrence of case build-up or outbreaks of epidemic-prone diseases.

Discussion

The overall health and nutrition emergency response in the Ranch collective site was coordinated and delivered by the Ranch onsite PHEOC which was established in Chagni town. The primary aim of this coordination platform was to ensure that health and nutrition emergency responses are delivered

TABLE 1 Total number of morbidities diagnosed in Ranch collective site, Chagni, northwest Ethiopia, November 2020 to June 2021 ($N = 31{,}832$).

Disease type	<1 year	1–4 year	5–14 year	≥15 years	Total	Proportion
Pneumonia	368	837	536	2,444	4,185	13.1
Acute febrile illness	113	567	467	2,393	3,539	11.1
Intestinal parasite	242	564	854	1,363	3,023	9.5
Acute upper respiratory tract infection	458	902	426	655	2,442	7.7
Diarrhea (none bloody)	331	713	308	808	2,160	6.8
Dyspepsia	0	0	4	1,985	1,989	6.2
Ophthalmologic cases	111	383	447	915	1,856	5.8
Rheumatoid arthritis	0	60	7	1,650	1,717	5.4
Others medical illness	33	146	320	1,167	1,667	5.2
Mental health and psychosocial support	0	24	185	1,486	1,695	5.3
Scabies	124	433	199	698	1,454	4.6
Urinary tract infection	0	27	127	1,036	1,191	3.7
Bloody diarrhea	67	298	245	423	1,034	3.2
Dermatologic cases	28	77	125	689	918	2.9
Malaria (RDT confirmed)	38	177	111	441	766	2.4
Injury/accident, trauma	7	37	54	328	425	1.3
Migraine headache	0	0	6	398	404	1.3
Hypertension	0	0	0	304	304	1.0
Minor surgery	5	14	27	182	227	0.7
Wound Infection	4	11	21	141	176	0.6
Asthma	0	0	8	146	154	0.5
Sexually transmitted infections	0	0	0	138	138	0.4
Known HIV cases	0	0	4	104	108	0.3
Malnutrition U5 children (SAM and MAM)	10	111	0	0	121	0.4
Diabetes mellitus	0	0	2	83	85	0.3
Presumptive tuberculosis	0	0	7	42	49	0.2
Chronic liver disease	0	0	0	4	4	0.0
Total	1,938	5,381	4,490	20,022	31,832	100

according to national and international humanitarian response standards (8, 9). We structured the onsite PHEOC to carry out all the five-basic functions of EOC. The incident commander and/or the deputy had played basic managerial functions like organizing/assembling the PHEOC team, providing onsite training, preparing terms of reference, overseeing the day-to-day operation of the PHEOC, conducting discussions with state and non-state actors and receiving a command from the higher levels. This onsite coordination platform enabled us to deliver quality health and nutrition services for all groups of IDPs, as written in the emergency response plan. Besides, it allowed us to early understand public health needs and problems, response constraints and challenges in the camp.

Overall, 33,410 IDPs received essential health services from the clinic. However, despite a high incidence of epidemic-prone diseases in similar settings (10), there was no occurrence of an outbreak of measles, cholera, polio, meningitis, and pertussis in the Ranch camp. The averages daily outpatient visits in Ranch temporary clinic were higher than what most primary hospitals report in the Amhara region. These much health services had been delivered with few, but firmly committed health professionals. Also, specialized medical services had been delivered on an outreach basis, as well as through a referral system at the nearest hospitals. For instance, trachomatous trichiasis and cataract surgeries had been done for 30 and 8 ophthalmic patients, respectively. Not only this, sputum samples for tuberculosis (TB) had been collected from 120 presumptive TB cases and one pulmonary TB case was detected and 5 contacts were also screened negative. In addition, mental health services had been integrated within the clinic and delivered according to the WHO recommendation for mental health services in emergency settings (11). In this regard, the PHEOC team believes that health services had been delivered based on their needs and according to national and international standards and protocols (4, 9, 11–13). Also, a vibrant emergency logistics system had been in place that delivered an ample

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amount of emergency drugs and medical supplies at the right time for Ranch temporary clinic and Chagni hospital.

Under the WaSH operation section unit, a total of 194 trench latrine seats, 74 shower rooms and 50 hand washing facilities had been constructed at the Ranch IDP site. Although having an adequate number of WaSH facilities by itself was not a guarantee to keep the camp and environment free from human feces and solid wastes. Hence, conducting a regular compound sanitation campaign was mandatory to keep clean the settlement from any solid wastes. As well, latrine seats had been washed on daily bases through the coordinated efforts of community volunteers. The main challenge in this regard was inadequate water supply to wash latrines on daily bases. Interestingly, river water was available within a 50–70-meter distance and we fetched from it.

Even though the ratio of latrine seats to that of the IDPs was not comparable with the Sphere standards, the other elements of WaSH were as per the recommendation in Sphere Handbook (9). For instance, waiting time for the toilet was zero, all latrine seats were within acceptable distances from shelters, they had internal locks, easy to use and keep clean. As well, they were not suitable for fly and mosquito breeding, had minimal smell and had adequate space for different uses, which allowed for the dignified cleaning, drying and disposal of women's menstrual. Largely, there were no human feces present nor solid wastes accumulated around the shelters or settlements. In this regard, volunteer IDPs had a substantial contribution to creating clean and safe settlements to the extent of being role models for the surrounding residents.

As a whole, the major response challenges were shortage of health professionals to fulfill the IMS structure, scarcity/inflexibility of budget, shortage of ambulances, inadequate water supply for latrine and shower rooms, and limited experience in collective center management and humanitarian services. A study conducted in three Sub-Saharan African countries also revealed that insufficient knowledge and experience about the health care needs of displaced populations was a challenge in Somalia, Kenya and Ethiopia (2). Also, another study from Somalia reported that shortage of human resources and insufficient funding were among the major factors influencing humanitarian services (14). Besides, the roles and responsibilities of the region, zone, district, and facility were not clearly stated, understood, and agreed upon by the respective organizations. Hence, some governmental organizations were not happy to take responsibility for the emergency response, considering this humanitarian response as a regional responsibility. The negative effects of such misconception were resolved and/or minimized by engaging all levels of the health sector in the onsite PHEOC. Also, frequent discussions had been held with the respective organizational leaders regarding the humanitarian response and its challenges.

For future similar emergencies that need the coordinated efforts of all levels of the health sector, joint discussion by inter and intra-sectoral leaders should be held about the shared and/or individual roles and responsibilities in the emergency response. Perhaps, this kind of discussion would be more fruitful and valuable if it is conducted at the initial phase of the emergency with a binding agreement by top-level managers and each coordination level should be accountable as stated in the agreement. Another lesson we took is the importance of having a pool of health workers who are experienced in EOC and humanitarian operations that are readily available for anytime deployments in the region. Besides, we have to develop/customize standards for humanitarian response (WaSH, surveillance, RCCE, temporary clinic, etc), develop health and nutrition emergency response guidelines, training materials, terms of reference for onsite EOC, and develop a training curriculum entitled *Leading in Emergencies* for emergency leaders. Above all, there should be directives regarding financial, human and material resource mobilizations and utilization during emergency responses. This directive should answer the basic concept of EOC and its unique future to bypass any bureaucratic government structure that hinders or delays timely response, and all government bodies and humanitarian actors should legalize and deeply understand it. Another powerful lesson we took is the need to have pre-existing buildings and infrastructures that serve as a multi-purpose collective center. These "collective centers" can be built in selected areas of the region with easily modifiable rooms/designs to use for similar purposes like isolation/quarantine centers, epidemic treatment centers, warehouses, etc.

Conclusion and lessons learned

We adequately met the health and nutrition needs of the IDPs, as stated in the Sphere humanitarian handbook. We have got so many lessons from the emergency response. The most pertinent lessons are the importance of a strong Incident Management System and onsite coordination platforms like PHEOC in managing complex emergencies, the need to develop a training curriculum entitled *Leading in Emergencies* for key PHEM leaders, building multi-purpose collective centers with infrastructures, having a roster of experienced experts on humanitarian operations, develop humanitarian response standards, guidelines, TOR, training materials, directives and PHEOC legal framework regarding financial, human and material resource mobilizations and utilization during emergencies and risk/vulnerability driven preparedness plan are among the key determinants of effective response.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The Amhara Public Health Institute Ethical Review Committee has approved this study. Administrative permission to access and publish the data was obtained from the Amhara Public Health Institute administrative bodies. Written informed consent for participation was not required for this study.

Author contributions

TA, BB, and AA conceived and designed the response method, which was needed to establish an Offsite and Onsite PHEOC and they supervised and monitored the entire process of the emergency response. MA, BB, and AA were Offsite PHEOC Incident Response Leader, Incident Manager, and Deputy Incident Manager, respectively. TA and EH were Onsite PHEOC Incident Commander and Deputy Incident Commander respectively, and they were directly involved in humanitarian responses in the camp, daily operations, day-to-day data collection, response team assembly and overall coordination of the team in the camp. TA analyzed the data and wrote the first draft of the manuscript. BB and AA reviewed and modified the drafts of the manuscript. MH took part in the whole process of the response and reviewed and modified the drafts of the manuscript. MA also participated in the design, supervised, and monitored the whole process of the emergency response. All authors have read and approved the different study steps and the final version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Medical disaster response: A critical analysis of the 2010 Haiti earthquake

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Introduction: On January 12, 2010, a 7.0 magnitude earthquake struck the Republic of Haiti. The human cost was enormous—an estimated 316,000 people were killed, and a further 300,000 were injured. The scope of the disaster was matched by the scope of the response, which remains the largest multinational humanitarian response to date. An extensive scoping review of the relevant literature was undertaken, to identify studies that discussed the civilian and military disaster relief efforts. The aim was to highlight the key-lessons learned, that can be applied to future disaster response practise.

Methods: Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews guidance was followed. Seven scientific databases were searched, using consistent search terms—followed by an analysis of the existent Haitian literature. This process was supplemented by reviewing available grey literature. A total of 2,671 articles were reviewed, 106 of which were included in the study. In-depth analysis was structured, by aligning data to 12 key-domains, whilst also considering cross-sector interaction (Civilian-Civilian, Military-Military, and Civilian-Military). Dominant themes and lessons learned were identified and recorded in an online spreadsheet by an international research team. This study focuses on explicitly analysing the medical aspects of the humanitarian response.

Results: An unprecedented collaborative effort between non-governmental organisations, international militaries, and local stakeholders, led to a substantial number of disaster victims receiving life and limb-saving care. However, the response was not faultless. Relief efforts were complicated by large influxes of inexperienced actors, inadequate preliminary needs assessments, a lack of pre-existing policy regarding conduct and inter-agency collaboration, and limited consideration of post-disaster redevelopment during initial planning. Furthermore, one critical theme that bridged all aspects of the disaster response, was the failure of the international community to ensure Haitian involvement.

Conclusions: No modern disaster has yet been as devastating as the 2010 Haiti earthquake. Given the ongoing climate crisis, as well as the risks posed by armed conflict—this will not remain the case indefinitely. This systematic analysis of the combined civilian and military disaster response, offers vital evidence for informing future medical relief efforts—and provides considerable opportunity to advance knowledge pertaining to disaster response.

KEYWORDS

humanitarian response, disaster response, military humanitarianism, Haiti earthquake, United Nations disaster response

Introduction

The Republic of Haiti[1] is the first nation state to be founded by former slaves (3), after gaining independence from colonial rule in 1804 (2). Its history has been tumultuous—the nation has been marred by political instability, a number of *coups d'état*, dictatorial regimes, and international interventions and occupations (2). This, in addition to the imposition of neo-liberal economic and development policy, has resulted in economic fragility and drastic demographic alterations, over the course of Haiti's maturation as a sovereign state (1). The Haitian population has largely gravitated towards major cities, which have become increasingly congested—particularly the nation's capital, Port-au-Prince (1). To facilitate such increases in population density, significant developments in housing have been required—with efforts widely failing to adhere to safe standards of construction (1). Furthermore, the poverty rate within Haiti has increased from 50 to 80% (1, 2). Currently, Haiti has the lowest Gross Domestic Product (GDP) per capita in the Latin American and Caribbean region (4), and the 30th lowest GDP per capita on purchasing power parity, globally (5).

On January 12th, 2010, a 7.0-magnitude earthquake struck Haiti. Its epicentre was just 15.5 miles from the capital, Port-au-Prince (6). The earthquake, and the 52 significant aftershocks[2] that followed, were catastrophic (6). The human cost was enormous; as many as 316,000[3] people were killed, 300,000 more were injured, 2 million were displaced, and a total of 3 million were directly affected (7, 10–12). For Haiti, an already vulnerable state, this disaster was a "worst-case" scenario. The nation lost key government capacity and leadership, with both political and primary security force leaders being killed by the earthquake (12). It also lost function of its electricity grid, telecommunications network, air, and seaports (13). The earthquake caused extensive damage to Haiti's already limited infrastructure and response capability (6). Healthcare services were particularly vulnerable, given that prior to the disaster, 47% of Haitians lacked access to even basic medical care, and external organisations provided 75% of the nation's healthcare (14). Thirty of the forty-nine medical facilities, within the regions impacted by the earthquake, were either partially or completely destroyed (15)—including, the only national tertiary care centre (6). The combination of substantial structural damage, and the large numbers of traumatically injured earthquake victims, meant that the local health system was at extreme risk of being overwhelmed.

The international community, responded to this need *en masse*, mounting one of the largest humanitarian relief efforts to date (16). Assistance arrived rapidly, in large numbers, and with varying levels of capacity and skill (11). A multitude of actors offered assistance, including both civilian and military organisations (2). With so many different agencies being involved, it is clear that coordination and communication during relief efforts, was required. When armed forces are involved in a response, coordination can be divided into three categories: Civilian-Civilian, Civilian-Military, and Military-Military. In the context of this study, Civilian refers to any non-military actors—such as government agencies, United Nations (UN) organisations, and Non-Governmental Organisations (NGO). The UN states that "essential dialogue and interaction between civilian and military actors in humanitarian emergencies… is necessary to protect and promote humanitarian principles, avoid competition, minimise inconsistency, and when appropriate, pursue common goals" [(17), Paragraph 1].

This scoping review seeks to analyse the medical component of the complex international, multi-sector response—identifying dominant themes within relevant literature, as well as highlighting the key lessons learned. Particular emphasis has been placed on the interaction between civilian and military actors involved in medical relief efforts, with the aim of informing guidelines that can improve collaborative efforts in future disaster responses, and direct future research.

1 For detailed historical discussion of the Republic of Haiti, please see texts by Moore (1) and Vialpando (2).

2 Following the primary earthquake, a minimum of 52 aftershocks were recorded with a magnitude of at least 4.5 (6).

3 This is the official figure reported by the Haitian government (7)—although, this number is disputed. Others estimate the death toll to be around 160,000–230,000 (2, 8, 9).

TABLE 1 Search terms utilised.

Haiti*	Earthquake*
Disaster	Response
Plan	Management
Preparedness	Recovery
Relief	Risk
Emergency	Military
Military medicine	Humanitarian
International cooperation	After action
Disaster planning	Emergency health service
Surge capacity	Medical countermeasure

*These were required search terms. The remaining terms were utilised in conjunction with these core terms—in various combinations.

Methodology

Utilising library scientists, an extensive scoping review of the relevant literature was undertaken. This process was designed to be reproducible, and articles were gathered through conducting verified, systematic searches of seven scientific databases (PubMed, Medline, World of Science, Embase, CINAHL, PsycInfo, Google Scholar)—utilising consistent search terms (Table 1). Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) guidelines were followed (18). The review was undertaken between June 14th 2020 and October 4th 2021. The screening process was conducted, using Covidence systematic review screening software (https://www.covidence.org/, Veritas Health Innovation, Melbourne, Australia).

To establish the search terms (Table 1), two preliminary tasks were undertaken.

1) Structured interviews with:
   a. Senior Haitian civilian clinicians
      i. Dr. Louis-Franck Télémaque[4].
      ii. Dr. Frédéric Barau Déjean[5].
   b. United States (US) military personnel
      i. Professor David Polatty[6].
      ii. Captain Andrew Johnson[7].

2) Review of two key-reports, analysing the earthquake response:
   a. *Response to the Humanitarian Crisis in Haiti Following the 12 January 2010 Earthquake: Achievements, Challenges and Lessons to Be Learned* (6).
   b. *The U.S. Military Response to the 2010 Haiti Earthquake: Considerations for Army Leaders* (12).

This process enabled the identification of key-domains of analysis, for establishing the lessons learned during the disaster response. The following eligibility criteria, were designed to ensure adequate data capture from the multiple entities and non-academic institutions, that were substantially involved in the earthquake response—but have historically disseminated reports outside of the traditional peer-review process. Twelve domains were recognised as relevant: Humanitarian and Military Response, Communication, Coordination, Resources, Needs Assessment, Pre-Existing Policy, Workforce/Infrastructure Loss, Timeliness/Timing of Response, Expertise, Military/Political Interaction/Conflict, External and Unknown Factors, and Preventable Deaths. Inclusion criteria mirrored these, and literature was to be included if information corresponding to one or more of the key-domains was identified. Exclusion criteria were: if there was no information on civilian-military response; if the article was not focused on the earthquake response; if there was an overly clinical focus[8]; if the article focused on long-term recovery without discussing relief efforts; if the article was a duplicate; if the full-text was unavailable; or if the article was published before January 12th 2010.

An initial 2,336 studies were identified from the database searches, 511 of which were immediately excluded as duplicates. Following abstract screening, with each title and abstract screened by two members of the study team, an additional 1,697 articles were excluded. A subsequent full-text review was undertaken, with each document being reviewed by two study team members, for inclusion or exclusion. A further 73 articles were identified as ineligible during this stage of the review—the full-text of one article was irretrievable, and so this was also excluded. The Haitian literature was also assessed, in its entirety, for all articles related to the earthquake response. The initial search, for any studies related to earthquakes in Haiti, identified 272 articles. After full-text review, three articles were found to be related to the 2010 response, and were included.

This process was supplemented by grey literature reviews, to identify unclassified military documents for inclusion in the study. At this stage, some articles with an exclusively civilian focus were included for review. A further 58 articles were identified during this process, four of which were noted to be ineligible for inclusion in the study.

The reference lists of included articles were reviewed (backward snowballing), to determine if any cited

4 Chief of Surgery at *Hôpital de l'Universite d'Etat d'Haiti*, Haiti's tertiary referral hospital, during the 2010 earthquake response.

5 Director at the *Centre d'Information et de Formation en Administration de la Santé* (CIFAS/MSPP), the Haitian "Centre for Health Administration, Information, and Training".

6 Civilian Professor at the United States Naval War College, and director of the college's Civilian-Military Humanitarian Response Program.

7 Director of Medical Operations for the USNS Comfort, during the 2010 earthquake response.

8 This included case reports or case series.

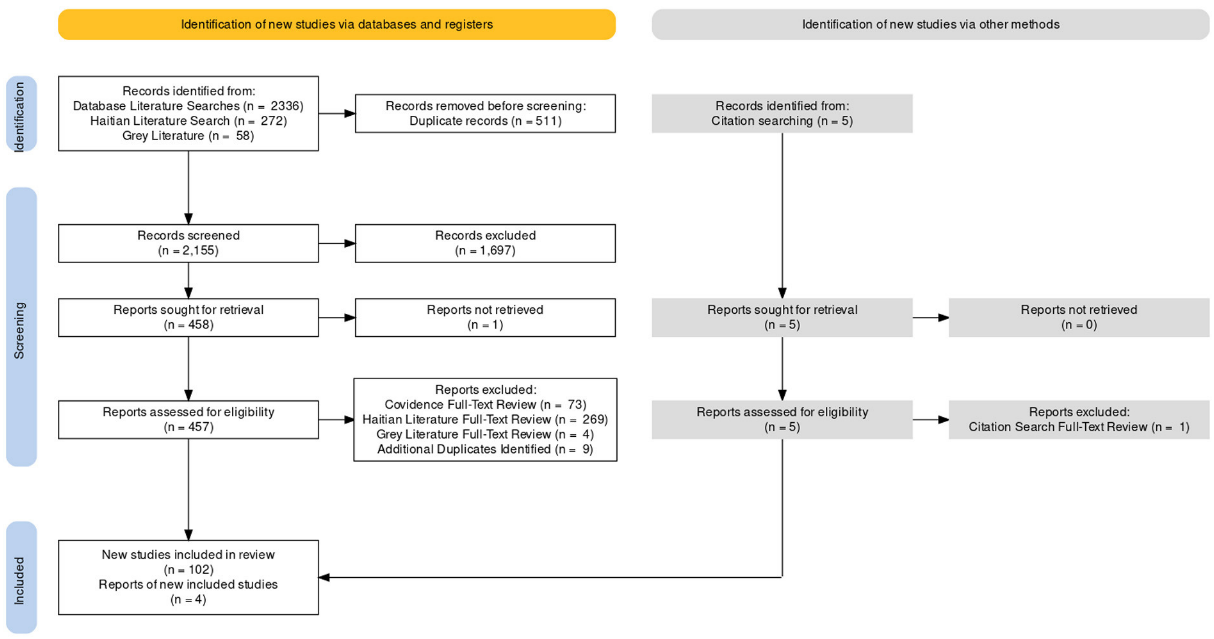

FIGURE 1
Preferred reporting items for systematic reviews and meta-analyses (PRISMA) flow diagram. A total of 106 articles were included. This flow diagram was created, using Evidence Synthesis Hackathon software (https://www.eshackathon.org/, Evidence Synthesis Hackathon).

works were eligible for inclusion—five additional studies were identified, four of which were included. Finally, citations of included articles were searched, to identify any relevant studies that had cited them (forward snowballing)—although, no further studies were included in this manner.

Nine additional studies were noted to be duplicates during the extraction process, and were subsequently excluded. The final number of articles, from which data was extracted, was 106 (Figure 1; Tables 2–5). In-depth analysis was structured by aligning data pertaining to the aforementioned 12 key-domains[9], and by sector-interaction (Civilian–Civilian, Military–Military, and Civilian–Military) (Figure 2). Dominant themes and lessons learned were identified and recorded, in an online table, by the ten reviewers. This data was then synthesised, and further examined, to focus more explicitly on medical elements of the response. This study will focus on the analysis of priority domains, the first 6 key-domains listed, as determined by the principal investigators (MJ and TW) (Figure 3).

9 These domains were identified and developed during the preliminary analysis (structured interviews and key-report analysis); the initial abstract and subsequent full-text reviews did not establish any additional domains.

Results

The humanitarian and military response

International dominance

The international response to the 2010 earthquake, constituted the largest humanitarian intervention carried out within a single nation (16). More than 140 governments, and over 1,000 NGOs, offered assistance (2, 9). A total of 26 nations sent military forces, the largest military cadre being that of the US (19)—who initially deployed 13,000 troops (20), a number that reached 22,000 during peak phases of the responses (2, 9, 19, 21).

The literature universally highlights the "International Nature" of the humanitarian response. Discussion encompasses international governments and the UN (16, 20, 22–25), international NGOs (2, 6, 19, 25–27), and international military organisations (9, 20, 24, 28–32)—predominantly, the activities of the US military (1, 2, 9, 13, 16, 19–21, 26, 31–59). What starkly manifests in the literature, is the paucity of discussion of the Haitian contribution to the response. There was limited inclusion of Haitian achievements—which, when discussed, consisted mainly of statements that work had been conducted alongside the Government of Haiti (GoH) (60), agreements and strategy had been formed with assistance from the GoH (36), or that support was to be provided to the GoH (24, 38, 44, 47). This is surprising, given that over 800 civil society organisations existed in Haiti, prior to the disaster (6).

TABLE 2 Database searches: articles included.

Title	Author(s)	Source
1 Canadian Field Hospital in Haiti: Surgical Experience in Earthquake Relief	Talbot, M., Meunier, B., Trottier, V., Christian, M., Hillier, T., Berger, C., McAlister, V., and Taylor, S.	Talbot, M., Meunier, B., Trottier, V., Christian, M., Hillier, T., Berger, C., et al. 1 Canadian Field Hospital in Haiti: Surgical Experience in Earthquake Relief. *Canadian Journal of Surgery*. 2012; 55(4): 271-274. Available at: https://dx.doi.org/10.1503/cjs.039010
A Call To Respond: The International Community's Obligation To Mitigate the Impact of Natural Disasters	Hernandez, J. R. and Johnson, A. D.	Hernandez, J. R., Johnson, A. D. A Call to Respond: The International Community's Obligation to Mitigate the Impact of Natural Disasters. *Emory International Law Review*. 2011; 25(3): 1087-1096. Available at: https://scholarlycommons.law.emory.edu/eilr/vol25/iss3/2
Actorness and Effectiveness in International Disaster Relief: The European Union and United States in Comparative Perspective	Brattberg, E. and Rhinard, M.	Brattberg, E., Rhinard, M. Actorness and Effectiveness in International Disaster Relief: The European Union and United States in Comparative Perspective. *International Relations*. 2013; 27(3): 356-374. Available at: https://dx.doi.org/10.1177/0047117813497298
Air Force Disaster Response: Haiti Experience	Stuart, J. J. and Johnson, D. C.	Stuart, J. J., Johnson, D. C. Air Force Disaster Response: Haiti Experience. *Journal of Orthopaedic Surgical Advances*. 2011; 20(1): 62-66. Available at: https://pubmed.ncbi.nlm.nih.gov/21477536/
Analysis of the International and US Response to the Haiti Earthquake: Recommendations for Change	Kirsch, T., Sauer, L., and Guha-Sapir, D.	Kirsch, T., Sauer, L., Guha-Sapir, D. Analysis of the International and US Response to the Haiti Earthquake: Recommendations for Change. *Disaster Medicine and Public Health Preparedness*. 2012; 6(3): 200-208. Available at: https://dx.doi.org/10.1001/dmp.2012.48
Application of Health Technology in Humanitarian Response: U.S. Military Deployed Health Technology Summit—A Summary	Doarn, C. R., Barrigan, C. R., and Poropatich, R. K.	Doarn, C. R., Barrigan, C. R., Poropatich, R. K. Application of Health Technology in Humanitarian Response: U.S. Military Deployed Health Technology Summit—A Summary. *Telemedicine and e-Health*. 2011; 17(16): 501-506. Available at: https://doi.org/10.1089/tmj.2011.0088
Beyond Command and Control: USSOUTHCOM's use of Social Networking to 'Connect and Collaborate' During Haiti Relief Operations	Arias, R.	Arias, R. Beyond Command and Control: USSOUTHCOM's Use of Social Networking to 'Connect and Collaborate' During Haiti Relief Operations. In: Kumar, B. V. K. V., Prabhakar, S., Ross, A. A., Southern, S. O., Montgomery, K. N., Taylor, C. W., et al. (eds.) *Proceedings of SPIE Defence, Security, and Sensing, Volume 8029: Sensing Technologies for Global Health, Military Medicine, Disaster Response, and Environmental Monitoring; and Biometric Technology for Human Identification VIII; 25th-27th April 2011; Orlando, Florida, United States*. Washington: SPIE; 2011. Available at: https://doi.org/10.1117/12.884734
Beyond Smokestacks and Silos: Open-Source, Web-Enabled Coordination in Organizations and Networks	Roberts, N. C.	Roberts, N. C. Beyond Smokestacks and Silos: Open-Source, Web-Enabled Coordination in Organizations and Networks. *Public Administration Review*. 2011; 71(5): 677-693. Available at: https://doi.org/10.1111/j.1540-6210.2011.02406.x
Catastrophe and Containment: A Critical Analysis of the US Response to the 2010 Earthquake in Haiti	Moore, A.	Moore, A. Catastrophe and Containment: A Critical Analysis of the US Response to the 2010 Earthquake in Haiti. In: Attinà, F. (ed.) *The Politics and Policies of Relief, Aid and Reconstruction*. Basingstoke: Palgrave Macmillan; 2012. p.113-132. Available at: https://dx.doi.org/10.1057/9781137026736_7
Civil–Military Collaboration in the Initial Medical Response to the Earthquake in Haiti	Auerbach, P. S., Norris, R. L., Menon, A. S., Brown, I. P., Kuah, S., Schwieger, J., Kinyon, J., Helderman, T. N., and Lawry, L.	Auerbach, P. S., Norris, R. L., Menon, A. S., Brown, I. P., Kuah, S., Schwieger, J., et al. Civil–Military Collaboration in the Initial Medical Response to the Earthquake in Haiti. *New England Journal of Medicine*. 2010; 362(10): e32. Available at: https://dx.doi.org/10.1056/nejmp1001555
Civilian-Military Pooling of Health Care Resources in Haiti: A Theory of Complementarities Perspective	Naor, M., Dey, A., Meyer-Goldstein, S., and Rosen, Y.	Naor, M., Dey, A., Meyer-Goldstein, S., Rosen, Y. Civilian-Military Pooling of Health Care Resources in Haiti: A Theory of Complementarities Perspective. *International Journal of Production Research*. 2018; 56(21): 6741-6757. Available at: https://dx.doi.org/10.1080/00207543.2017.1355121

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TABLE 2 (Continued)

Title	Author(s)	Source
Collaboration in Humanitarian Logistics: Comparative Analysis of Disaster Response in Chile and Haiti 2010	Allende, V. and Anaya, J.	Allende, V., Anaya, J. *Collaboration in Humanitarian Logistics: Comparative Analysis of Disaster Response in Chile and Haiti 2010* [Master's Thesis]. California: Naval Postgraduate School; 2010. Available at: https://calhoun.nps.edu/handle/10945/10482
Collaborative Geospatial Data as Applied to Disaster Relief: Haiti 2010	Clark, A. J., Holliday, P., Chau, R., Eisenberg, H., and Chau, M.	Clark, A. J., Holliday, P., Chau, R., Eisenberg, H., Chau, M. Collaborative Geospatial Data as Applied to Disaster Relief: Haiti 2010. In: Kim, T.-h., Fang, W.-c., Khan, M. K., Arnett, K. P., Kang, H.-j., Slęzak, D. (eds.) *Security Technology, Disaster Recovery and Business Continuity*. Communications in Computer and Information Science. Vol 122. Berlin, Germany: Springer; 2010. p.250-258. Available at: https://doi.org/10.1007/978-3-642-17610-4_29
Comparative Analysis of Emergency Response Operations: Haiti Earthquake in January 2010 and Pakistan's Flood in 2010	Niazi, J.I.K.	Niazi, J. I. K. *Comparative Analysis of Emergency Response Operations: Haiti Earthquake in January 2010 and Pakistan's Flood in 2010* [Master's Thesis]. California: Naval Postgraduate School; 2011. Available at: http://hdl.handle.net/10945/5516
Comparative Performance of Alternative Humanitarian Logistic Structures after the Port-au-Prince Earthquake: ACEs, PIEs, and CANs	Holguín-Veras, J., Jaller, M., and Wachtendorf, T.	Holguín-Veras, J., Jaller, M., Wachtendorf, T. Comparative Performance of Alternative Humanitarian Logistic Structures after the Port-Au-Prince Earthquake: ACEs, PIEs, and CANs. *Transportation Research Part A: Policy and Practice*. 2012; 46(10): 1623-1640. Available at: https://www.sciencedirect.com/science/article/pii/S0965856412001322
Coping with the Challenges of Early Disaster Response: 24 Years of Field Hospital Experience After Earthquakes	Bar-On, E., Abargel, A., Peleg, K., and Kreiss, Y.	Bar-On, E., Abargel, A., Peleg, K., Kreiss, Y. Coping with the Challenges of Early Disaster Response: 24 Years of Field Hospital Experience after Earthquakes. *Disaster Medicine and Public Health Preparedness*. 2013; 7(5): 491-498. Available at: https://dx.doi.org/10.1017/dmp.2013.94
Deployment of Field Hospitals to Disaster Regions: Insights from Ten Medical Relief Operations Spanning Three Decades	Naor, M., Heyman, S. N., Bader, T., and Merin, O.	Naor, M., Heyman, S. N., Bader, T., Merin, O. Deployment of Field Hospitals to Disaster Regions: Insights from Ten Medical Relief Operations Spanning Three Decades. *American Journal of Disaster Medicine*. 2017; 12(4): 243-256. Available at: https://doi.org/10.5055/ajdm.2017.0277
Dilemmas for Disaster Relief – The Cases of Myanmar, Haiti and Aceh through the Lens of National Sovereignty and International Intervention	Rucktäschel, K. and Schlegel, S.	Rucktäschel, K., Schlegel, S. Dilemmas for Disaster Relief—the Cases of Myanmar, Haiti and Aceh through the Lens of National Sovereignty and International Intervention. In: Neuhäuser, C., Schuck, C. (eds.) *Military Interventions: Considerations from Philosophy and Political Science*. 1st ed. Baden-Baden: Nomos Verlagsgesellschaft; 2017. p.107-128.
Disaster Aeromedical Evacuation	Lezama, N. G., Riddles, L. M., Pollan, W. A., and Profenna, L. C.	Lezama, N. G., Riddles, L. M., Pollan, W. A., Profenna, L. C. Disaster Aeromedical Evacuation. *Military Medicine*. 2011; 176(10): 1128-1132. Available at: https://dx.doi.org/10.7205/milmed-d-11-00040
Early Disaster Response in Haiti: The Israeli Field Hospital Experience	Kreiss, Y., Merin, O., Peleg, K., Levy, G., Vinker, S., Sagi, R., Abargel, A., Bartal, C., Lin, G., Bar, A., Bar-On, E., Schwaber, M.J., and Ash, N.	Kreiss, Y., Merin, O., Peleg, K., Levy, G., Vinker, S., Sagi, R., et al. Early Disaster Response in Haiti: The Israeli Field Hospital Experience. *Annals of Internal Medicine*. 2010; 153(1): 45-48. Available at: https://www.acpjournals.org/doi/abs/10.7326/0003-4819-153-1-201007060-00253
Emergency Knowledge Management and Social Media Technologies: A Case Study of the 2010 Haitian Earthquake	Yates, D. and Paquette, S.	Yates, D., Paquette, S. Emergency Knowledge Management and Social Media Technologies: A Case Study of the 2010 Haitian Earthquake. *International Journal of Information Management*. 2011; 31(1): 6-13. Available at: https://doi.org/10.1016/j.ijinfomgt.2010.10.001
Emerging Powers, Humanitarian Assistance and Foreign Policy: The Case of Brazil During the Earthquake Crisis in Haiti	Aguilar, S. L. C.	Aguilar, S. L. C. Emerging Powers, Humanitarian Assistance and Foreign Policy: The Case of Brazil During the Earthquake Crisis in Haiti. *International Journal of Humanities and Social Science*. 2012; 2(19): 93-101. Available at: http://hdl.handle.net/11449/115496

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TABLE 2 (Continued)

Title	Author(s)	Source
'Going Back to History': Haiti and US Military Humanitarian Knowledge Production	Greenburg, J.	Greenburg, J. 'Going Back to History': Haiti and US Military Humanitarian Knowledge Production. *Critical Military Studies*. 2018; 4(2): 121-139. Available at: https://dx.doi.org/10.1080/23337486.2017.1313380
Haiti Earthquake: Crisis and Response	Margesson, R. and Taft-Morales, M.	Margesson, R., Taft-Morales, M. *Haiti Earthquake: Crisis and Response* [Online] District of Columbia: Congressional Research Service; 2010. Available at: https://apps.dtic.mil/sti/citations/ADA516429
Haiti Relief: An International Effort Enabled through Air, Space, and Cyberspace	Fraser, D. M. and Hertzelle, W. S.	Fraser, D. M., Hertzelle, W. S. Haiti Relief: An International Effort Enabled through Air, Space, and Cyberspace. *Air & Space Power Journal*. 2010; 24(4): 5-12. Available at: https://apps.dtic.mil/sti/citations/ADA533555
Haiti: The US and Military Aid in Times of Natural Disaster (ARI)	Encina, C.G.	Encina, C. G. *Haiti: The US and Military Aid in Times of Natural Disaster (ARI)*. [Online] Madrid: Real Instituto Elcano; 2010. Available at: https://media.realinstitutoelcano.org/wp-content/uploads/2021/11/ari57-2010-garciaencina-haiti-us-militray-aid-natural-disaster.pdf
Haitian Earthquake Relief: Disaster Response Aboard the USNS Comfort	Walk, R. M., Donahue, T. F., Stockinger, Z., Knudson, M. M., Cubano, M., Sharpe, R. P., and Safford, S.D.	Walk, R. M., Donahue, T. F., Stockinger, Z., Knudson, M. M., Cubano, M., Sharpe, R. P., et al. Haitian Earthquake Relief: Disaster Response Aboard the USNS Comfort. *Disaster Medicine and Public Health Preparedness*. 2012; 6(4): 370-377. Available at: https://dx.doi.org/10.1001/dmp.2012.67
Healthcare Delivery Aboard Us Navy Hospital Ships Following Earthquake Disasters: Implications for Future Disaster Relief Missions	Sechriest II, V. F., Wing, V., Walker, G. J., Aubuchon, M., and Lhowe, D. W.	Sechriest II, V. F., Wing, V., Walker, G. J., Aubuchon, M., Lhowe, D. W. Healthcare Delivery Aboard US Navy Hospital Ships Following Earthquake Disasters: Implications for Future Disaster Relief Missions. *American Journal of Disaster Medicine*. 2012; 7(4): 281-294. Available at: https://doi.org/10.5055/ajdm.2012.0101
How Negotiations Within the Humanitarian Arena Shape the Effectiveness of the Coordination of Disaster Response: A Literature Review of the Indian Ocean Earthquake of 2004 in Indonesia and the Haitian Earthquake of 2010 in Haiti	Hoving, J. K.	Hoving, J. K. *How Negotiations within the Humanitarian Arena Shape the Effectiveness of the Coordination of Disaster Response: A Literature Review of the Indian Ocean Earthquake of 2004 in Indonesia and the Haitian Earthquake of 2010 in Haiti* [Master's Thesis]. Wageningen: Wageningen University; 2016. Available at: https://regroup-production.s3.amazonaws.com/documents/ReviewReference/213890334/edepotair_t58072658_001.pdf?response-content-type=application%2Fpdf&X-Amz-Algorithm=AWS4-HMAC-SHA256&X-Amz-Credential=AKIAYSFKCAWY23RWESRS%2F20220716%2Fus-east-1%2Fs3%2Faws4_request&X-Amz-Date=20220716T000639Z&X-Amz-Expires=604800&X-Amz-SignedHeaders=host&X-Amz-Signature=5dafeda35f1618009ba1343a799e2f511f4c1efc31c6e06362b66fa9926a47e9
Humanitarian Relief in Haiti, 2010: Honing the Partnership between the US Air Force and the UN	Owen, R. C.	Owen, R. C. Humanitarian Relief in Haiti, 2010: Honing the Partnership between the US Air Force and the UN. In: Dorn, A. W. (ed.) *Air Power in UN Operations: Wings for Peace*. 1st ed. Surrey: Ashgate Publishing; 2014. p.77-101. Available at: https://doi.org/10.4324/9781315566313
Independent Review of the U.S. Government Response to the Haiti Earthquake	Guha-Sapir, D., Kirsch, T., Dooling, S., Sirois, A., and DerSarkissian, M.	Guha-Sapir, D., Kirsch, T., Dooling, S., Sirois, A., DerSarkissian, M. *Independent Review of the U.S. Government Response to the Haiti Earthquake*. [Online] District of Columbia: United States Agency for International Development; 2011. Available at: https://pdf.usaid.gov/pdf_docs/pdacr222.pdf
Italy's Military Interventions and New Security Threats: The Cases of Somalia, Darfur and Haiti	Ceccorulli, M. and Coticchia, F.	Ceccorulli, M., Coticchia, F. Italy's Military Interventions and New Security Threats: The Cases of Somalia, Darfur and Haiti. *Contemporary Politics*. 2016; 22(4): 412-431. Available at: https://doi.org/10.1080/13569775.2016.1175095
Lessons from the Humanitarian Disaster Logistics Management: A Case Study of the Earthquake in Haiti	Salam, M. A. and Khan, S. A.	Salam, M. A., Khan, S. A. Lessons from the Humanitarian Disaster Logistics Management: A Case Study of the Earthquake in Haiti. *Benchmarking: An International Journal*. 2020; 27(4): 1455–1473. Available at: https://doi.org/10.1108/BIJ-04-2019-0165

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TABLE 2 (Continued)

Title	Author(s)	Source
Managing Airborne Relief During International Disasters	Morales, M. and Sandlin, D.E.	Morales, M., Sandlin, D. E. Managing Airborne Relief During International Disasters. *Journal of Humanitarian Logistics and Supply Chain Management*. 2015; 5(1): 12-34. Available at: https://doi.org/10.1108/JHLSCM-01-2014-0008
Military and Humanitarian Cooperation in Air Operations in Haiti	Whiting, M.C.	Whiting, M. C. Military and Humanitarian Cooperation in Air Operations in Haiti. *Humanitarian Exchange* [Online] 2012. February; 2012(53): 35-37. Available at: https://odihpn.org/wp-content/uploads/2012/03/humanitarianexchange053.pdf
Mobilizing for International Disaster Relief: Comparing U.S. and EU Approaches to the 2010 Haiti Earthquake	Brattberg, E. and Sundelius, B.	Brattberg, E., Sundelius, B. Mobilizing for International Disaster Relief: Comparing U.S. And EU Approaches to the 2010 Haiti Earthquake. *Journal of Homeland Security and Emergency Management*. 2011; 8(1): 0000102202154773551869. Available at: https://doi.org/10.2202/1547-7355.1869
Orthopedic Activity in Field Hospitals Following Earthquakes in Nepal and Haiti	Bar-On, E., Blumberg, N., Joshi, A., Gam, A., Peyser, A., Lee, E., Kashichawa, S.K., Morose, A., Schein, O., Lehavi, A., Kreiss, Y., and Bader, T.	Bar-On, E., Blumberg, N., Joshi, A., Gam, A., Peyser, A., Lee, E., et al. Orthopedic Activity in Field Hospitals Following Earthquakes in Nepal and Haiti. *World Journal of Surgery*. 2016; 40(9): 2117-2122. Available at: https://dx.doi.org/10.1007/s00268-016-3581-3
Partnered Disaster Preparedness: Lessons Learned From International Events	Born, C. T., Cullison, T. R., Dean, J. A., Hayda, R. A., McSwain, N., Riddles, L. M., and Shimkus, A. J.	Born, C. T., Cullison, T. R., Dean, J. A., Hayda, R. A., McSwain, N., Riddles, L. M., et al. Partnered Disaster Preparedness: Lessons Learned from International Events. *Journal of the American Academy of Orthopaedic Surgeons*. 2011; 19: S44-S48. Available at: https://journals.lww.com/jaaos/Fulltext/2011/02001/Partnered_Disaster_Preparedness__Lessons_Learned.10.aspx
Planning the Unplanned: The Role of a Forward Scout Team in Disaster Areas	Tarif, B., Merin, O., Dagan, D., and Yitzhak, A.	Tarif, B., Merin, O., Dagan, D., Yitzhak, A. Planning the Unplanned: The Role of a Forward Scout Team in Disaster Areas. *International Journal of Disaster Risk Reduction*. 2016; 19: 25-28. Available at: https://www.sciencedirect.com/science/article/pii/S2212420916302060
Relationships Matter: Humanitarian Assistance and Disaster Relief in Haiti	Keen, P. K., Neto, F. P. V., Nolan, C. W., Kimmey, J. L., and Althouse, J.	Keen, P. K., Neto, F. P. V., Nolan, C. W., Kimmey, J. L., Althouse, J. Relationships Matter: Humanitarian Assistance and Disaster Relief in Haiti. *Military Review*. 2010: 2-12. Available at: https://www.armyupress.army.mil/Portals/7/military-review/Archives/English/MilitaryReview_20100630_art004.pdf
Responding to Haiti	Dutton, G.	Dutton, G. Responding to Haiti. *World Trade*. 2010; 23(2): 16-17.
Response to the Humanitarian Crisis in Haiti Following the 12 January 2010 Earthquake: Achievements, Challenges and Lessons to Be Learned	Inter-Agency Standing Committee	Inter-Agency Standing Committee. *Response to the Humanitarian Crisis in Haiti Following the 12 January 2010 Earthquake: Achievements, Challenges and Lessons to Be Learned.* [Online] Geneva: Inter-Agency Standing Committee; 2010. Available at: https://reliefweb.int/report/haiti/response-humanitarian-crisis-haiti-following-12-january-2010-earthquake-achievements
Semantic and Social Networks Comparison for the Haiti Earthquake Relief Operations from APAN Data Sources Using Lexical Link Analysis (LLA)	Zhao, Y., Gallup, S.P., and MacKinnon, D.J.	Zhao, Y., Gallup, S. P., MacKinnon, D. J. Semantic and Social Networks Comparison for the Haiti Earthquake Relief Operations from APAN Data Sources Using Lexical Link Analysis (LLA). In: *Proceedings of the 17th International Command and Control Research and Technology Symposium (ICCRTS); 19th-21st June 2012; Fairfax, Virginia, United States*: ICCRTS; 2012. Available at: http://hdl.handle.net/10945/37505
Successes and Challenges of the Haiti Earthquake Response: The Experience of USAID	Weisenfeld, P. E.	Weisenfeld, P. E. Successes and Challenges of the Haiti Earthquake Response: The Experience of USAID. *Emory International Law Review*. 2011; 25(3): 1097-1120. Available at: https://scholarlycommons.law.emory.edu/eilr/vol25/iss3/3/
Telecommunications in Israeli Field Hospitals Deployed to Three Crisis Zones	Finestone, A. S., Levy, G., and Bar-Dayan, Y.	Finestone, A. S., Levy, G., Bar-Dayan, Y. Telecommunications in Israeli Field Hospitals Deployed to Three Crisis Zones. *Disasters*. 2014; 38(4): 833-845. Available at: https://dx.doi.org/10.1111/disa.12074

(Continued)

TABLE 2 (Continued)

Title	Author(s)	Source
The Effects of Stabilisation on Humanitarian Action in Haiti	Muggah, R.	Muggah, R. The Effects of Stabilisation on Humanitarian Action in Haiti. *Disasters*. 2010; 34(S3): S444-S463. Available at: https://dx.doi.org/10.1111/j.1467-7717.2010.01205.x
The Haiti Earthquake Operation: Real Time Evaluation for the International Federation of Red Corss and Red Crescent Societies	Fisher, M., Bhattacharjee, A., Saenz, J., and Schimmelpfennig, S.	Fisher, M., Bhattacharjee, A., Saenz, J., Schimmelpfennig, S. *The Haiti Earthquake Operation: Real Time Evaluation for the International Federation of Red Corss and Red Crescent Societies*. [Online] Geneva: International Federation of Red Cross and Red Crescent Societies; 2010. Available at: https://www.ifrc.org/media/13753
The Islanding Effect: Post-Disaster Mobility Systems and Humanitarian Logistics in Haiti	Sheller, M.	Sheller, M. The Islanding Effect: Post-Disaster Mobility Systems and Humanitarian Logistics in Haiti. *Cultural Geographies*. 2013; 20(2): 185-204. Available at: https://dx.doi.org/10.1177/1474474012438828
The Use of Volunteer Interpreters During the 2010 Haiti Earthquake: Lessons Learned from the Usns Comfort Operation Unified Response Haiti	Powell, C. and Pagliara-Miller, C.	Powell, C., Pagliara-Miller, C. The Use of Volunteer Interpreters During the 2010 Haiti Earthquake: Lessons Learned from the Usns Comfort Operation Unified Response Haiti. *American Journal of Disaster Medicine*. 2012; 7(1): 37-47. Available at: https://doi.org/10.5055/ajdm.2012.0079
Tradeoffs Among Attributes of Resources in Humanitarian Operations: Evidence from United States Navy	Apte, A., Bacolod, M., and Carmichael, R.	Apte, A., Bacolod, M., Carmichael, R. Tradeoffs among Attributes of Resources in Humanitarian Operations: Evidence from United States Navy. *Production and Operations Management*. 2020; 29(4): 1071-1090. Available at: https://dx.doi.org/10.1111/poms.13154
Understanding Government Decision-Making: Canada's Disaster-Relief in Haiti and Pakistan	Mamuji, A. A.	Mamuji, A. A. *Understanding Government Decision-Making: Canada's Disaster-Relief in Haiti and Pakistan* [Doctoral Dissertation]. Ottawa: University of Ottawa; 2014. Available at: https://ruor.uottawa.ca/bitstream/10393/31704/5/Mamuji_Aaida_2014_thesis.pdf
United Nations–European Union Cooperation in Aid, Relief and Reconstruction — The Haiti Case	Morsut, C. and Iturre, M. J.	Morsut, C., Iturre, M. J. United Nations–European Union Cooperation in Aid, Relief and Reconstruction — the Haiti Case. In: Attinà, F. (ed.) *The Politics and Policies of Relief, Aid and Reconstruction*. London: Palgrave Macmillan; 2012. p.133-150. Available at: https://dx.doi.org/10.1057/9781137026736_8
Using Web 2.0 Technology to Support Humanitarian Assistance and Disaster Relief Operations: Applying the Lessons Learnt from the United States Military Response to the 2010 Haiti Earthquake to Improve the Utilisation of the New Zealand Defence Force's Communications and Information Systems During Humanitarian Assistance and Disaster Relief Operations	Jones, L. S.	Jones, L. S. *Using Web 2.0 Technology to Support Humanitarian Assistance and Disaster Relief Operations: Applying the Lessons Learnt from the United States Military Response to the 2010 Haiti Earthquake to Improve the Utilisation of the New Zealand Defence Force's Communications and Information Systems During Humanitarian Assistance and Disaster Relief Operations* [Master's Thesis]. Manawatu: Massey University; 2011. Available at: https://mro.massey.ac.nz/bitstream/handle/10179/4265/02_whole.pdf

Listed alphabetically, by article title.

The medical response

The 2010 earthquake resulted in over 316,000 deaths, and 300,000 injured casualties (12). This inordinate burden of traumatically injured patients, initially overwhelmed local facilities (29). Therefore, a core aspect of the humanitarian response was to facilitate delivery of emergency medical care to the victims. The enormity of the medical efforts undertaken during this response, cannot be overstated. Twenty-four days after the earthquake occurred, 91 hospitals, including 21 Foreign Field Hospitals (FFH), and five hospital ships, were operational within Haiti (14) (Tables 6–8).

Military-humanitarian response

In total, 26 nations contributed military personnel, the largest of which was the US (19)—whose joint effort was termed, Operation Unified Response (OUR). During OUR, the joint components of the US military delivered health care to around 19,000 victims, performed 1,025 operations, and provided

TABLE 3 Grey literature: Articles included.

Title	Author(s)	Source
22d MEU Unified Response CONOP Brief	22nd Marine Expeditionary Unit	**Grey literature:** 22nd Marine Expeditionary Unit. *22d MEU Unified Response CONOP Brief*. [Presentation] United States Southern Command. 19th January 2010.
Action Memorandum: Operation Unified Response Quick-Look Assessment Report	Haley, J.R.	**Grey literature:** Haley, J. R. *Action Memorandum: Operation Unified Response Quick-Look Assessment Report*. 15th March 2010.
After Action Review - Operation Unified Response, Lessons Learned: SCJ4 Operational Contract Support	United States Southern Command	**Grey literature:** United States Southern Command. *After Action Review - Operation Unified Response, Lessons Learned: SCJ4 Operational Contract Support*. Florida: United States Southern Command: 2010.
Building Habitability Assessment Plan	Joint Task Force-Haiti	**Grey literature:** Joint Task Force-Haiti. *Building Habitability Assessment Plan*. [Presentation] 2010.
Commander United States Southern Command Executive Order, 18 January 2010	Commander United States Southern Command	**Grey literature:** Commander United States Southern Command. *Commander United States Southern Command Executive Order, 18 January 2010*. Florida: United States Southern Command; 18th January 2010.
Commander United States Southern Command For Official Use Only, Order 16 January 2010	Commander United States Southern Command	**Grey literature:** Commander United States Southern Command. *Commander United States Southern Command for Official Use Only, Order 16 January 2010*. Florida: United States Southern Command; 16th January 2010.
Consolidated Southern Command Fragmentary Orders: Lessons Learned	Commander 4th Fleet	**Grey literature:** Commander 4th Fleet. *Consolidated Southern Command Fragmentary Orders: Lessons Learned*. Florida: United States Southern Command; 2010. Report Number: 091.
Department of Defense Support to Foreign Disaster Relief: Handbook for JTF Commanders and Below	United States Department of Defense	**Grey literature:** United States Department of Defense. *Department of Defense Support to Foreign Disaster Relief: Handbook for JTF Commanders and Below*. District of Columbia: United States Government Printing Office; 2011.
Draft: Operation Unified Response (OUR) AAR	United States Southern Command	**Grey literature:** United States Southern Command. *Draft: Opeartion Unified Response (OUR) AAR*. [Presentation] United States Southern Command. 2010.
Emergency Response after the Haiti Earthquake: Choices, Obstacles and Finance	Médecins Sans Frontières	**Grey literature:** Médecins Sans Frontières. *Emergency Response after the Haiti Earthquake: Choices, Obstacles and Finance.* [Online] Geneva: Médecins Sans Frontières; 2010. Available at: https://www.msf.org/emergency-response-after-haiti-earthquake-choices-obstacles-and-finance
Haiti after the Disaster – Lessons learned from Evaluations, Consequences and Recommendations for the Future of Swiss Humanitarian Aid	Tobler, C., Hasler, N., and Chastonay, C.	**Grey literature:** Tobler, C., Hasler, N., Chastonay, C. *Haiti after the Disaster – Lessons Learned from Evaluations, Consequences and Recommendations for the Future of Swiss Humanitarian Aid* [Unpublished Coursework]. St. Gallen: University of St. Gallen; 2011.
Haiti Earthquake After Action Report and Lessons Learned (AAR/LL): Hastily Formed Networks in Haiti	Steckler, B.	**Grey literature:** Steckler, B. *Haiti Earthquake After Action Report and Lessons Learned (AAR/LL): Hastily Formed Networks in Haiti.* California: Naval Postgraduate School, Hastily Formed Networks Center; 8th September 2010. Available at: https://nps.edu/documents/105738171/0/Haiti$+$Earthquake$+$AAR-LL$+$Document$+$-$+$Steckler$+$NPS$+$HFN$+$Center$+$-$+$10$+$SEP$+$2010.pdf/caceb389-e228-495d-bc89-d8d7cfd79f64
Haiti Earthquake Relief: One-Year Report	American Red Cross	**Grey literature:** American Red Cross. *Haiti Earthquake Relief: One-Year Report*. [Online] District of Columbia: American Red Cross; 2011. Available at: https://www.redcross.org/content/dam/redcross/atg/PDF_s/HaitiEarthquake_OneYearReport.pdf
Haiti Lessons Learned: Operation Unified Response	Branch, T.	**Grey literature:** Branch, T. *Haiti Lessons Learned: Operation Unified Response*. [Presentation] Carrier Strike Group 1. 8th April 2010.
Haiti: Carrier Strike Group-1 Operations Order	Commander Carrier Strike Group-1	**Grey literature:** Commander Carrier Strike Group-1. *Haiti: Carrier Strike Group-1 Operations Order*. California: United States 3rd Fleet; 15th January 2010. Report Number: 100116.

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TABLE 3 (Continued)

Title	Author(s)	Source
Health Response to the Earthquake in Haiti: January 2010	Goyet, C. d. V. d., Sarmiento, J. P., and Grünewald, F.	**Grey literature:** Goyet, C. d. V. d., Sarmiento, J. P., Grünewald, F. *Health Response to the Earthquake in Haiti: January 2010*. [Online] Washington: Pan American Health Organization; 2011. Available at: https://iris.paho.org/bitstream/handle/10665.2/52841/9789275132524_eng.pdf?sequence=1&isAllowed=y
HQ USSOUTHCOM: Operation Unified Response AAR	United States Southern Command	**Grey literature:** United States Southern Command. *HQ USSOUTHCOM: Operation Unified Response AAR*. [Presentation] United States Southern Command. 10th May 2010.
JTF-Haiti Recommendation to Release USNS Comfort	United States Southern Command	**Grey literature:** United States Southern Command. *JTF-Haiti Recommendation to Release USNS Comfort* [Presentation] United States Southern Command. 25th February 2010.
JTF-Haiti: CVN Departure Assessment	United States Southern Command	**Grey literature:** United States Southern Command. *JTF-Haiti: CVN Departure Assessment*. [Presentation] United States Southern Command. 26th January 2010.
Meeting Minutes: Joint Chiefs of Staff Brief 19th January 2010	Joint Chiefs of Staff	**Grey literature:** Joint Chiefs of Staff. *Meeting Minutes: Joint Chiefs of Staff Brief 19th January 2010*. District of Columbia: United States Department of Defense; 19th January 2010.
Memorandum for Heads of Executive Departments and Agencies: Special Solicitation for Haitian Earthquake Relief	Berry, J.	**Grey literature:** Berry, J. *Memorandum for Heads of Executive Departments and Agencies: Special Solicitation for Haitian Earthquake Relief*. District of Columbia: United States Office of Personnel Management; 14th January 2010.
Minutes of the Meeting of Joint Task Force-Haiti Commander's Conference	Commander 4th Fleet	**Grey literature:** Commander 4th Fleet. *Minutes of the Meeting of Joint Task Force-Haiti Commander's Conference*. Florida: United States Naval Forces Southern Command; 13th February 2010.
Modification 1 to United States Southern Command Executive Order: Operation Unified Response	Fraser, D.	**Grey literature:** Fraser, D. *Modification 1 to United States Southern Command Executive Order: Operation Unified Response*. Florida: United States Southern Command; 17th January 2010. Report Number: MSG/CDRUSSOUTHCOM/161330ZJAN10.
Modification 4 to United States Southern Command Executive Order: Operation Unified Response	Fraser, D.	**Grey literature:** Fraser, D. *Modification 4 to United States Southern Command Executive Order: Operation Unified Response*. Florida: United States Southern Command; 19th January 20110. Report Number: MSG/CDRUSSOUTHCOM/190032ZJAN10.
Operation Haiti Relief: After Action Report	Florida State Emergency Response Team	**Grey literature:** Florida State Emergency Response Team. *Operation Haiti Relief: After Action Report*. Florida: Florida Division of Emergency Management; 2010.
Operation Unified Response – Haiti Earthquake 2010	DiOrio, D.R.	**Grey literature:** DiOrio, D. R. *Operation Unified Response – Haiti Earthquake 2010*. [Online] Virginia: Joint Forces Staff College; 2010. Available at: https://jfsc.ndu.edu/Portals/72/Documents/JC2IOS/Additional_Reading/4A_Haiti_HADR_Case_Study_revNov10.pdf
Operation Unified Response (Haiti Earthquake): After Action Report	United States Coast Guard: Atlantic Area	**Grey literature:** United States Coast Guard: Atlantic Area. *Operation Unified Response (Haiti Earthquake): After Action Report*. Virginia: United States Coast Guard; 2011.
Operation Unified Response (Haiti Earthquake): After Action Review	7th Sustainment Brigade	**Grey literature:** 7th Sustainment Brigade. *Operation Unified Response (Haiti Earthquake): After Action Review*. 23rd June 2010.
Operation Unified Response (Haiti): CDR's Update Brief	Commander United States Naval Forves Southern Command	**Grey literature:** Commander United States Naval Forves Southern Command. *Operation Unified Response (Haiti): CDR's Update Brief*. [Presentation] United States Naval Forces Southern Command. 20th Jan 2010.
Operation Unified Response (OUR): Compendium of USAF Reports	Henningsen, J. R. (Editor)	**Grey literature:** Henningsen, J. R. (ed.) *Operation Unified Response (OUR): Compendium of USAF Reports*. District of Columbia: United States Air Force, Studies and Analyses, Assessments and Lessons Learned; 2011.
Operation Unified Response: A Case Study of the Military's Role in Disaster Relief Operations	Hughes, T. D.	**Grey literature:** Hughes, T. D. *Operation Unified Response: A Case Study of the Military's Role in Disaster Relief Operations* [Master's Thesis]. Virginia: Marine Corps University; 2011. Available at: https://apps.dtic.mil/sti/pdfs/ADA600734.pdf

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TABLE 3 (Continued)

Title	Author(s)	Source
Operation Unified Response: Air Mobility Command's Response to the 2010 Haiti Earthquake Crisis	Wallwork, E. D., Gunn, K. S., Morgan, M. L., and Wilcoxson, K. A.	**Grey literature:** Wallwork, E. D., Gunn, K. S., Morgan, M. L., Wilcoxson, K. A. *Operation Unified Response: Air Mobility Command's Response to the 2010 Haiti Earthquake Crisis*. [Online] Illinois: Office of History, Air Mobility Command; 2010. Available at: https://www.amc.af.mil/Portals/12/documents/AFD-131018-050.pdf
Operation Unified Response: Haiti Earthquake Response	Joint Center for Operational Analysis	**Grey literature:** Joint Center for Operational Analysis. *Operation Unified Response: Haiti Earthquake Response*. [Presentation] Joint Center for Operational Analysis. May 2010.
Operation Unified Response: Haiti Earthquake Situation Update	United States Department of Defense	**Grey literature:** United States Department of Defense. *Operation Unified Response: Haiti Earthquake Situation Update*. [Presentation] District of Columbia: United States Department of Defense. 19th January 2010.
Operation Unified Response: Humanitarian Assistance Response Force (HARF)	Commander United States Southern Command	**Grey literature:** Commander United States Southern Command. *Operation Unified Response: Humanitarian Assistance Response Force (HARF)*. [Presentation] United States Southern Command. 19th February 2010.
Operation Unified Response: Joint Task Force Port Opening/Commander Task Force 42	United States Southern Command	**Grey literature:** United States Southern Command. *Operation Unified Response: Joint Task Force Port Opening/Commander Task Force 42*. [Presentation] United States Southern Command. 12th February 2010.
Operation Unified Response: JTF-H Concept Brief	Campbell, J.	**Grey literature:** Campbell, J. *Operation Unified Response: JTF-H Concept Brief*. [Presentation] United States Southern Command. 22nd January 2010.
Operation Unified Response: Transition Strategy	United States Southern Command	**Grey literature:** United States Southern Command. *Operation Unified Response: Transition Strategy*. [Presentation] United States Southern Command. 12th February 2010.
Operation Unified Response: Transition to Long Term Engagement	Alvirez, S.	**Grey literature:** Alvirez, S. *Operation Unified Response: Transition to Long Term Engagement*. [Presentation] United States Southern Command. 2010.
Proceedings for Operation Unified Response – Haiti Navy Medicine After Action Review	Valentin, E. V. (Editor)	**Grey literature:** Valentin, E. V. (ed.) Proceedings for Operation Unified Response – Haiti Navy Medicine After Action Review. *Operation Unified Response – Haiti Navy Medicine After Action Review; 5th-6th May 2010*; Maryland, United States. Texas: Navy Medicine Support Command; 2010.
Public Health Risk Assessment and Interventions - Earthquake: Haiti	World Health Organisation	**Grey literature:** World Health Organisation. *Public Health Risk Assessment and Interventions - Earthquake: Haiti*. [Online] Geneva: World Health Organisation: Disease Control in Humanitarian Emergencies; 2010. Available at: https://reliefweb.int/report/haiti/public-health-risk-assessment-and-interventions-earthquake-haiti-21-january-2010
Some Challenges and Considerations in Forming a Joint Task Force	Joint Center for Operational Analysis	**Grey literature:** Joint Center for Operational Analysis. *USSOUTHCOM and JTF-Haiti: Some Challenges and Considerations in Forming a Joint Task Force*. Virginia: United States Joint Forces Command; 2010.
Stability Operations in Haiti 2010: A Case Study	Vialpando, E.	**Grey literature:** Vialpando, E. *Stability Operations in Haiti 2010: A Case Study*. [Online] Pennsylvania: Peacekeeping and Stability Operations Institute; 2016. Available at: https://publications.armywarcollege.edu/pubs/3306.pdf
The U.S. Military Response to the 2010 Haiti Earthquake: Considerations for Army Leaders	Cecchine, G., Morgan, F. E., Wermuth, M. A., Jackson, T., Schaefer, A. G., and Stafford, M.	**Grey literature:** Cecchine, G., Morgan, F. E., Wermuth, M. A., Jackson, T., Schaefer, A. G., Stafford, M. *The U.S. Military Response to the 2010 Haiti Earthquake: Considerations for Army Leaders*. [Online] California: RAND Corporation; 2013. Available at: https://www.rand.org/pubs/research_reports/RR304.html
USAID Haiti Earthquake Taskforce: (SBU) Situation Report No. 11	United States Agency for International Development	**Grey literature:** United States Agency for International Development. *USAID Haiti Earthquake Taskforce: (SBU) Situation Report No. 11*. District of Columbia: United States Agency for International Development; 18th January 2010. Report Number: 11.
USAID Knowledge Services Center (KSC): Lessons Learned from the 2005 Pakistan Earthquake	United States Agency for International Development	**Grey literature:** United States Agency for International Development. *USAID Knowledge Services Center (KSC): Lessons Learned from the 2005 Pakistan Earthquake*. [Online] District of Columbia: United States Agency for International Development: Knowledge Services Center; 2010. Available at: https://pdf.usaid.gov/pdf_docs/PNADM100.pdf

Listed alphabetically, by article title.

TABLE 4 Haitian literature search: Articles included.

Title	Author(s)	Source
Anaesthetic Safety, from Humanitarian to Development	Fabien, D.	**Haitian literature:** Fabien, D. Anaesthetic Safety, from Humanitarian to Development. *INFO-CHIR: La Revue Haitienne de Chirurgie et d'Anesthésiologie*. 2012; 2(8): 19-21.
Culturally Competent Volunteer Becomes a Partner after the Earthquake	Tascoe. R. M.	**Haitian literature:** Tascoe. R. M. Culturally Competent Volunteer Becomes a Partner after the Earthquake. *INFO-CHIR: La Revue Haitienne de Chirurgie et d'Anesthésiologie*. 2011; 1 (4): 29-33.
Genitourinary Trauma in Disaster Situations: The Haitian Earthquake of January 12, 2010	Gousse, A. E.	**Haitian literature:** Gousse, A. E. Genitourinary Trauma in Disaster Situations: The Haitian Earthquake of January 12, 2010. *INFO-CHIR: La Revue Haitienne de Chirurgie et d'Anesthésiologie*. 2011; 1(4): 4-7.

Listed alphabetically, by article title.

TABLE 5 Citation searches: Articles included.

Title	Author(s)	Source
Foreign Disaster Response: Joint Task Force–Haiti Observations	Keen, P. K., Elledge, M. G., Nolan, C. W., and Kimmey, J. L.	**Citation search:** Keen, P. K., Elledge, M. G., Nolan, C. W., Kimmey, J. L. Foreign Disaster Response: Joint Task Force–Haiti Observations. *Military Review*. 2010; November-December: 85-96. Available at: https://apps.dtic.mil/sti/citations/ADA537030
Haiti Earthquake 2010: One-Year Progress Report	International Federation of Red Cross And Red Crescent Societies	**Citation search:** International Federation of Red Cross And Red Crescent Societies. *Haiti Earthquake 2010: One-Year Progress Report*. [Online] Geneva: International Federation of Red Cross And Red Crescent Societies; 2011. Available at: https://reliefweb.int/report/haiti/haiti-earthquake-2010-one-year-progress-report
The Logistic Experience of the Brazilian Navy in Humanitarian Operations: The Cases of Earthquakes in Haiti and Chile in 2010	Mendonça, B. G. S. G. d., Paula-Filho, A. B. d., and Leiras, A.	**Citation search:** Mendonça, B. G. S. G. d., Paula-Filho, A. B. d., Leiras, A. The Logistic Experience of the Brazilian Navy in Humanitarian Operations: The Cases of Earthquakes in Haiti and Chile in 2010. *Production*. 2019; 29: e20170082. Available at: https://dx.doi.org/10.1590/0103-6513.20170061
The United Nations Humanitarian Civil–Military Coordination (UN–CMCoord) Response to the Haiti Earthquake	Butterfield, A., Reario, R., and Dolan, R.	**Citation search:** Butterfield, A., Reario, R., Dolan, R. *The United Nations Humanitarian Civil–Military Coordination (UN–CMCoord) Response to the Haiti Earthquake*. Humanitarian Exchange [Online] 2010. October; 2010(48): 13-15. Available at: https://odihpn.org/wp-content/uploads/2010/08/humanitarianexchange048.pdf

Listed alphabetically, by article title.

FIGURE 2
Sector interaction.

FIGURE 3
Priority domains.

70,000 medical prescriptions (9). They also participated in 2,200 patient transfers and distributed around 75 tonnes of medical equipment (9).

The US Air Force (USAF) provided initial medical response and evacuation capabilities (33) within 24 h of the disaster (40). The initial response unit consisted of an Air Force Special Operation Command (AFSOC) team—supported by surgical,

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TABLE 6 Summary of healthcare operations: United States military.

	Operation Unified Response	AFSOC	USS Bataan (22nd MEU)	USS Carl Vinson	USNS Comfort	SPEARR	EMEDS (6th air mobility wing)	USS Nassau (24th MEU)
Date of Arrival	January 13th	January 13th	January 18th	January 15th	January 20th	Initial Team: January 23rd Replacement Team: Mid-March	January 24th	January 23rd
Date of Departure	Officially Concluded June 1st 2010	January 23rd	March 25th	February 1st	March 10th	June 1st	March 19th	February 9th
Capacity	Ships Deployed: 33 Aircraft Deployed: 130	–	Overflow Beds: 540 Ward Beds: 47 ICU Beds: 17 Operating theatres: 6	Total Beds: 50 ICU Beds: 8–9	Total Beds: 1,000 CASREC Beds: 50 ICU Beds: 60–80 Recovery Beds: 20 Operating Theatres: 12–20	Critical Care Beds: 10 ICU Beds: 3	Ward Beds: 20 Critical Care Beds: 3 Operating Theatres: 1	–
Staffing	Max Personnel: 22,000	–	GS: 3 T&O: 2 O&G: 1 O/MF:1 AN: 3 SN: 1	–	Total Medical Personnel: ≈ 400 Interpreters: 130 (57 Navy, 73 ARC)	Total: 12 T&O: 1 GS: 1 AN: 1 EM: 1 PH: 1 IM: 1 AeSp: 1 SN: 1 CCN: 1 CPT: 1 BMS: 1 PHT:1	Total: 78 Surgical Team: 5 T&O: 1 GS: 1 AN: 1 EM: 1 SN: 1	-
Patients Triaged	–	8,000	–	–		–	–	–
Patients Treated	19,000	362	47	–	Total: 872 Outpatient: 55	–	2,500	>100
Surgical Operations	Procedures: 1,025	Procedures: 14	Procedures: 109	–	Procedures: 927 - Patients: 454 - Extremity Injuries: 669 - Craniofacial Reconstruction: 93	Procedures: 10 - Not performed at airport site - Surgeons volunteered at local NGO units	Procedures: 12	–
Primary Specialties by % of Operative Cases	–	–	T&O: 55% GS: 29%	–	T&O: 55% GS: 9%	–	–	–
Amputations	–	9	4	–	Primary Amputations: 37 Revision Surgeries: 105 (58 Patients)	–	–	–

(Continued)

TABLE 6 (Continued)

	Operation Unified Response	AFSOC	USS Bataan (22nd MEU)	USS Carl Vinson	USNS Comfort	SPEARR	EMEDS (6th air mobility wing)	USS Nassau (24th MEU)
Inpatient Admissions	–	–	–	–	Total: 817 Haitian Nationals: 773 US Military: 26 US Civilians: 15 Canadian Military: 3	–	150	–
Patient Transfers	2,200	–	–	–	Transferred to Haitian Facilities for Continued Care: 448	–	500	–
Evacuations	Medical Evacuations: 343 US Citizen Evacuations: 16,412	Total: 167	Total: 500	–	Total Evacuated to US: 77 Haitians Evacuated to US: 69	Total: 498	–	–

"–", Information Unavailable; ICU, Intensive Care Unit; GS, General Surgery/Surgeon; T&O, Trauma and Orthopaedics/Trauma and Orthopaedic Surgeon; O&G, Obstetrician and Gynaecologist; O/MF, Oral and Maxillofacial Surgery/Surgeon; AN, Anaesthetics/Anaesthetist; EM, Emergency Physician(s); PH, Public Health Specialist; IM, Internal Medicine Physician(s); M&D, Medical and Dental; AeSp, Aerospace Medical Specialist(s); SN, Scrub Nurse(s)/Theatre Nurse(s); CCN, Critical Care Nurse(s); CPT, Cardiopulmonary Technician(s); BMS, Biomedical Scientist(s); PHT, Public Health Technician(s); ARC, American Red Cross; DRC, Dominican Red Cross; NRC, Norwegian Red Cross.

critical care, and medical assets (40). Of the AFSOC teams deployed, one remained at the airport with the critical care and evacuation team (Figure 4), whilst the other responded to the American embassy (40). The embassy team triaged over 8,000 American citizens, treated 362 patients, and performed 14 major operations, 9 of which were amputations (40). The Small Portable Expeditionary Aeromedical Rapid Response (SPEARR) team, arrived on January 23rd and replaced the initial AFSOC team at *Port-au-Prince-Toussaint L'Ouverture International Airport* (MTPP) (40). The SPEARR team consisted of twelve members, who evacuated 498 patients over their 2-month deployment (40). The final USAF asset deployed, was the 78-member team, of the Expeditionary Medical Support (EMEDS) system (40). EMEDS personnel arrived on January 24th, primarily setting up at a private seaport, Terminal Varreux (40). Their team treated over 2,500 patients-—150 of which required inpatient admission—participated in over 500 patient transfers, and conducted 12 operative procedures (40).

Within 4 days of the earthquake, the US Navy (USN) was able to begin treating patients on the USS Carl Vinson (47) (Figure 5). Following this, the largest sea-based asset involved in the disaster response, the hospital ship USNS Comfort (29), arrived January 20th, with tertiary care capability. The USNS Comfort's capabilities included at least 30 medical sub-specialties, supplemented by physiotherapists, nurse practitioners, midwives and physician's assistants—totalling almost 400 medical staff (39). Over 90% of the US military's surgical procedures were carried out onboard, the vast majority of which, were for extremity injuries (39). Of the injuries that presented, 45% were fractures–9% of the operative procedures performed were external fixations, and 14% of were primary internal fixations (61). Of the patients treated onboard the Comfort, 69% were adults, and 26% were children (61). The USS Bataan supported the USNS Comfort, arriving within 12 days of the disaster (47). Personnel onboard the USS Bataan treated 47 surgical patients, 87% of whom had sustained injuries related to the disaster, conducting a total of 109 surgical procedures (61). Of their total caseload, 72% of the patients were adults, 21% of the patients were children, 41% of the total injuries sustained were fractures, and amputations made up 3% of the operative procedures (61). The most active specialty involved in patient encounters were Trauma and Orthopaedic (T&O) surgeons, primarily treating 55% of the patients on both the USS Bataan, and the USNS Comfort (61). Furthermore, dental and medical professionals of the 24th Marine Expeditionary Unit (MEU), of the USS Nassau, treated over 100 Haitians (2). The care provided at sea, was supported on shore, through the opening of an aftercare facility (9). Within the Port-au-Prince area, infantry units from the 82nd Airborne Division, "helped facilitate emergency medical services by establishing trauma care facilities, delivering critical medical supplies, providing security at aid stations, and facilitating the transfer of injured patients" [(2), p. 62] to international facilities.

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TABLE 7 Summary of healthcare operations: international military organisations—non-US.

	Spanish Armed Forces (Castilla)	French Armed Forces (Siroco)	Military Forces of Colombia (Cartagena de Indias)	Mexican Armed Forces (Huasteco)	Canadian Armed Forces (HMCS Athabaskan)	Brazilian Air Force Foreign Field Hospital	Israel Defense Forces Foreign Field Hospital	Canadian Armed Forces Foreign Field Hospital
Date of arrival	February 4th	January 24th	January 22nd	January 20th	January 19th	–	January 13th	January 29th
Date of Departure	May 4th	February 6th	February 14th	–	–	–		
Capacity	Total Beds: 70 Ward Beds: 62 ICU Beds: 8 Operating Theatres: 2	Total Beds: 50 Operating Theatres: 2	Operating Theatres: 1	Total Beds: 25 Operating Theatres: 1	–		–	Ward Beds: 100 ICU Beds: 4 Operating Theatres: 2
Staffing		–	Physicians: 8	–	Total: 250–300	Physicians: 26	Total: 121 Physicians: 44	M&D Personnel: 97 Surgical Teams: 2 T&O: 1 GS: 1 AN: 1 SN: 1
Patients Triaged	–	–	–	–	–	–	–	–
Patients Treated	7,568	–	200	–	–	36,028	1,111 Fractures: 265	4,922
Inpatient Admissions	–	–			–	–	737	–
Surgical Operations	Procedures: 104	Procedures: 45	Procedures: 27	–	–	1,145	Procedures: 244	Procedures: 167 Inguinal Hernia and Hydrocoele Repairs: 69 Internal Fixation: 12 External Fixation: 7
Primary Specialties by % of Operative Cases	–	–	–	–	–	–	T&O: 83%	–
Amputations	–	–	–	–	–	–	–	6
Patient Transfers	–	–	–	–	–	–	–	-
Evacuations	–	–	–	–	–	–	–	–

"–", Information Unavailable; ICU, Intensive Care Unit; GS, General Surgery/Surgeon; T&O, Trauma and Orthopaedics/Trauma and Orthopaedic Surgeon; O&G, Obstetrician and Gynaecologist; O/MF, Oral and Maxillofacial Surgery/Surgeon; AN, Anaesthetics/Anaesthetist; EM, Emergency Physician(s); PH, Public Health Specialist; IM, Internal Medicine Physician(s); M&D, Medical and Dental; AeSp, Aerospace Medical Specialist(s); SN, Scrub Nurse(s)/Theatre Nurse(s); CCN, Critical Care Nurse(s); CPT, Cardiopulmonary Technician(s); BMS, Biomedical Scientist(s); PHT, Public Health Technician(s); ARC, American Red Cross; DRC, Dominican Red Cross; NRC, Norwegian Red Cross.

TABLE 8 Summary of healthcare operations: international organisations—civilian.

	Médecins Sans Frontières	The International Federation of Red Cross and Red Crescent Societies	Dominican Republic Emergency Teams	University of Miami Project Medishare Hospital	Cuban Medical Brigade
Date of arrival	January 13th	January 12th (DRC)	January 12th	January 21st	January 12th
Date of departure	–	–	–	–	–
Capacity	Hospitals: 2 Fixed Sites: 19 Mobile Units: 3 Total Beds: 1,187 Operating Theatres: 16	FFH: 2 FFH (NRC) - Total Beds: 20 Basic Health Care Units: 4 Fixed Sites: 4 Mobile Units: 41	–	250	–
Staffing	Haitian Staff: 2,807 International Staff: 209	FFH (NRC) Personnel: 30 Surgical Teams: 2 Outpatient Teams: 1 Haitian Volunteers Trained: 20 Mental Health, 110 Vaccinators	–	Total: 12	Total: 1,500
Patients triaged	–	–	–	–	Within 1st 24 h: 1,000 Total: 20,095
Patients treated	173,757	216,900	2,000	–	14,551
Inpatient admissions	–	–	–		
Surgical operations	11,748	1,339 FFH (NRC): 300	–	–	1,252
Primary specialties by % of operative cases	–	–	–	–	–
Amputations	Within 1st 20 Days: 140	–	–	–	–
Patient transfers	–	–	–	–	–
Evacuations	–	–	–	–	–

"–", Information Unavailable; ICU, Intensive Care Unit; GS, General Surgery/Surgeon; T&O, Trauma and Orthopaedics/Trauma and Orthopaedic Surgeon; O&G, Obstetrician and Gynaecologist; O/MF, Oral and Maxillofacial Surgery/Surgeon; AN, Anaesthetics/Anaesthetist; EM, Emergency Physician(s); PH, Public Health Specialist; IM, Internal Medicine Physician(s); M&D, Medical and Dental; AeSp, Aerospace Medical Specialist(s); SN, Scrub Nurse(s)/Theatre Nurse(s); CCN, Critical Care Nurse(s); CPT, Cardiopulmonary Technician(s); BMS, Biomedical Scientist(s); PHT, Public Health Technician(s); ARC, American Red Cross; DRC, Dominican Red Cross; NRC, Norwegian Red Cross.

A number of other militaries contributed to the medical response in varying capacities. Colombia, France, Mexico and Spain also sent hospital ships, most of which were deployed for under a month (14). The Spanish ship, the Castilla, remained for a total of 64 days–28 more than the USNS Comfort (14). The vessel had capacity for 70 beds in total, including eight intensive care unit (ICU) beds (14). Medical professionals saw a total of 7,568 patients, reviewed initially at a land based mobile health unit, and conducted 104 surgical procedures (14). Both Canadian and Israeli military forces, utilised FFHs in the disaster response (28, 62), which are rapidly deployable treatment facilities. The Israeli military had previously developed an airborne field hospital model, that was structured to function in disaster settings (29). It utilised self-sufficient and flexible capabilities (29), with a total of 120 staff (62). Their workforce was composed of experienced and inexperienced personnel[10], with the intention of facilitating knowledge transfer during relief efforts (29) (Figure 6). They also augmented work force capacity, by incorporating eight clinical staff from Colombia, which allowed them to run a total of four operating theatres (29). This unit initially functioned as a tertiary medical centre, until the USNS Comfort arrived (29). The Israeli Defense Force's (IDF) hospital was functional within 3 days of the earthquake (28), admitting their first patient at 10:00 a.m. on January 16th (63). The IDF offloaded the overburdened local health system,

10 Two-thirds of the team had existing experience, whilst one-third were junior staff, who had not been involved in previous disaster responses (29).

FIGURE 4
Inside the AFSOC medical tent, U.S. Air Force AFSOC Commander Lt. Gen. Donald C. Wurster visits with his troops at the Toussaint Louverture International Airport, Port-au-Prince, Haiti, on January 27 during Operation Unified Response. DoD assets have been deployed to assist in the Haiti relief effort following a magnitude 7 earthquake that hit the city on January 12. The appearance of U.S. DoD visual information does not imply or constitute DoD endorsement. Source: Public domain image, not in copyright. Available at: https://commons.wikimedia.org/wiki/File:Operation_Unified_Response_DVIDS244961.jpg.

FIGURE 5
A medical response team aboard the Nimitz-class aircraft carrier USS Carl Vinson (CVN 70) transports a Haitian patient to an operating room after being flown aboard by helicopter. Carl Vinson and Carrier Air Wing 17 are conducting humanitarian and disaster relief operations as part of Operation Unified Response after a 7.0 magnitude earthquake caused severe damage near Port-au-Prince, Haiti, January 12, 2010 (U.S. Navy photo by Mass Communication Specialist 2nd Class Daniel Barker/Released). The appearance of U.S. DoD visual information does not imply or constitute DoD endorsement. Source: Public domain image, not in copyright. Available at: https://commons.wikimedia.org/wiki/File:USS_Carl_Vinson_relief_operations_100112-N-RI884-065.jpg.

by dealing with patients who had suffered injuries directly pertaining to the earthquake. They treated 1,111 patients, admitted 737, and performed 265 operations (63, 64). In the first 3 days of operation, ∼80% of presentations were due to traumatic injury (63). Of those patients admitted, 66% had sustained trauma, and of these, 46% had fracture injuries (64). The most active specialty was T&O, who conducted 83% of the operative procedures undertaken (64). In the case of the Canadian FFH, which arrived in Haiti after 17 days, the caseload encountered was predominantly patients (over 80%) who were not directly injured by the earthquake (28). During the 48-day deployment of the Canadian FFH, 151 patients received a total of 167 operative procedures (28). Of the operations performed at this facility, the overwhelming majority were inguinal hernia and hydrocoele repairs (28).

FIGURE 6
OC Home Front Command, Maj. Gen. Yair Golan, pictured here on a visit to the IDF Field Hospital in the premature baby maternity ward. After the devastating earthquake which struck Haiti in January 2010, Israel sent an aid delegation of over 250 personnel to help with search and rescue efforts and establish a field hospital in Port-au-Prince. Source: Public domain image, not in copyright. Available at: https://commons.wikimedia.org/wiki/File:Flickr_-_Israel_Defense_Forces_-_Head_of_Home_Front_Command_Visits_Aid_Delegation.jpg.

Civilian-humanitarian response

Of the civilian-based responses, the most comprehensive documentation was provided by *Médecins Sans Frontières* (MSF) and the International Federation of Red Cross and Red Crescent Societies (IFRC) (10, 27). The responses documented by both MSF and the IFRC, encompassed not only the initial emergency period, but also detailed efforts of the post-disaster response and re-development process. Further to this, the Cuban Medical Brigade (CMB) and academic institutions, participated in relief efforts—as well as medical professionals of the Haitian diaspora (14).

MSF, the "largest provider of emergency surgical care" during the humanitarian intervention [(14), p. 73], had staff in Haiti at the time of the earthquake. Therefore, their initial response began within hours (27). This included, evacuating patients from existing units, searching for appropriate facilities to continue care, and assessing new casualties—which sometimes had to occur in office spaces (27). In the early stages of the response, finding specialist treatment for the complex trauma patients, was imperative. MSF facilitated this by transferring patients to the Dominican Republic (DR) by helicopter (27). Although support staff arrived within 18 h of the disaster, difficulties were still encountered. Notably, the lack of available emergency medical equipment, such as drills, for use in burr hole procedures (27). This was compounded by logistical issues, with 11 out of 17 flights bringing personnel and supplies, having been diverted in the first 6 days (27). This meant deliveries had to arrive by road, from the DR, resulting in substantial delays (27, 41). Despite this, during the first 20 days of the emergency response, MSF clinicians had undertaken 1,300 operations, 140 of which were extremity amputations (27). The majority of surgical procedures conducted in the first month, were wound debridement and orthopaedic interventions (14). Early on in relief efforts, MSF partnered with the Renal Disaster Relief Task Force (RDRTF)—enabling a fully functioning dialysis centre, to be established 5 days after the earthquake (14, 65). Four and a half months into the response, 19 health facilities[11], with over 1,000 available beds, were being managed by MSF; over 170,000 patients had been treated[12], and 11,748 surgical procedures had been conducted (27).

The response of the Dominican Red Cross was immediate, dispatching a volunteer cadre across the Haitian border (10). The IFRC deployed two mobile field hospitals, and four basic healthcare units (11). They also managed a further 41 mobile, and five fixed health facilities (10, 11). By June, they had treated 95,500 patients, the majority of which received care for "non-communicable diseases and everyday emergencies" [(10), p. 34], and conducted a total of 1,339 surgical procedures. Additionally, they had extensive community-based healthcare programmes, reaching over 9,000 patients through these outreach initiatives, and provided vaccines to 150,000 Haitians (10). The CMB, who had an established presence in Haiti since 1998, had 330 healthcare personnel in the country at the onset of the crisis (14). They were able to begin assessing patients within 90 min, and conducted 1,000 emergency medical reviews in the first 24 h (14). They had access to a broad range of specialties, and 14 operating theatres—their staff also included colleagues from Canada, Chile, Colombia, Spain, Mexico and Venezuela (66). By January 27th, the CMB had delivered care to 14,551 patients and conducted 1,252 surgical procedures (66)—throughout the response, over 1,500 personnel from CMB were involved in delivering healthcare (14). Other specialised medical organisations that contributed to the emergency response, included Merlin and *Médecins du Monde* (11)—but there was little discussion of their activities. Moreover, it was noted that an initial restriction in capacity to provide post-operative care, meant that only a few life-saving emergency surgical operations could take place in the immediate post-earthquake period (11).

Six academic medical institutions from Chicago, participated in the medical response (14). By April 1st, the Chicago initiative had deployed 158 volunteers for minimum periods of 2 weeks and were integrated into established medical NGOs (14). The Harvard Humanitarian Program, led by "Partners in Health", a non-profit organisation, operated across nine medical locations (14). By June 19th, 50 medical and surgical professionals had been dispatched along with medical, surgical, and anaesthetic supplies (14). During the initial 9 days of the response, the University of Miami's "Project Medishare" hospital, was based inside the UN compound. Its 250-bed capacity was staffed by only 12 individuals, and had no critical care or surgical capabilities (14). This was then transferred to a four-tent facility at MTPP, manned by 220 volunteer workers, rotating over 7-day intervals, with capacity for a specialist spinal care unit (14). This collaborative institution, utilised robust administrative and logistical capabilities, "coordinating flights to transport medical staff, supplies, equipment and victims between Haiti and the United States" [(14), p. 49]. The contribution of diaspora Haitian medical professionals was briefly discussed. Sixty clinicians from the Association of Haitian Doctors Abroad, were integrated into the *Hôpital d l'Universite d'Etat d'Haiti* (Haiti's University and Educational Hospital—HUEH) workforce on January 16th, setting up the initial emergency care unit at the institution (14).

MSF worked closely alongside Haitian clinical staff, in delivering medical assistance throughout the response (27). Although initially, recruitment issues were noted, in total they employed 2,807 Haitian staff—over 90% of their workforce—including doctors, nurses, administrators, project coordinators, drivers and logisticians (27). Furthermore, MSF also considered developing medical skill sets during the disaster response, an analogous approach to that of the IDF. The civilian organisation aimed to work with Haitian clinicians to "reintroduce... techniques" that they had been unable to utilise, due to a lack of surgical equipment [(27), p. 17]. The IFRC, similarly experienced issues recruiting staff in the early phases of the response—however, by June 2010, were employing over 1,000 Haitian national staff (10). A further example of local involvement, was the CMB's utilisation of Haitian medical students and interns—who were completing their training in Cuba at the time of the disaster (66). Humanitarian agencies, more generally, were noted to recruit large numbers of Haitian doctors, paying "salaries several times (higher than) their pre-disaster incomes" [(14), p. 39]—which, although a common practise in humanitarian responses, has detrimental implications for the host nations health systems and recovery.

11 At the peak of their operations, two months into the response, MSF were overseeing 26 individual facilities—one of these units, that was running throughout the entire response, was a fully functioning inflatable hospital (27).

12 This included care delivered to patients who had presented with non-earthquake related pathology (27).

Haitian-humanitarian response

An estimated burden of 30,000 genitourinary injury cases was reported in the Haitian peer-reviewed literature (67). In correlation with foreign opinion, better coordination was deemed essential for the implementation of "mobile disaster-specific medical units with tools to help disaster specific injuries—such as crush syndrome and spinal cord injury after earthquake—are paramount to improve patient survival" [(67), p. 6]. The same report, highlighted the new disaster-related medical and social needs affecting a significant proportion of the population, requiring long-term treatment and infrastructure.

The Department of Anaesthetics at HUEH reported on this transition process. In 2012, an evaluation conducted after a substantial number of humanitarian NGOs had left Haiti, found the burden of restructuring and development while attempting to uphold quality of care, taxing and slow. The lack of sufficient standard operating procedures, human resources, and clinical staff, caused disorganisation in the delivery of surgical care—further perpetuated by healthcare providers leaving Haiti, or acquiring relatively well-paid NGO employment (68) (Figure 7). The need for central governance was highlighted as a potential solution to improving the delivery of safe patient care: "with the efforts of our health authorities, the wealth of our human resources, and the help of external cooperation, we can achieve the interdependence that is our mark of respect for ourselves and our patients, in order to ensure the safety and quality of care that we desire" [(68), p. 21].

FIGURE 7
Medical personnel transport a Haitian woman and her new-born son to the post-operating room at the University Hospital in Port-Au-Prince, Haiti, January 20, 2010. VIRIN: 100120-n-6070s-016. Photograph: Petty Officer 2nd Class Justin Stumberg, USN. Source: Public domain image, not in copyright. Available at: https://commons.wikimedia.org/wiki/File:Newborn_baby_%26_mother_moved_to_post-op_at_University_Hospital,_Port-au-Prince_2010-01-20.jpg.

Medical response: Additional themes

Readjusting healthcare priorities

The healthcare needs of the Haitian population evolved as relief efforts matured, and the priorities of the humanitarian mission had to change to mirror these (9, 27, 29, 40, 59). The IDF, and both the Canadian and US military, recognised that patient levels and presentations altered as the response continued (28, 29, 40, 59). The Canadian FFH had noted, that during the disaster response, the majority of their operative caseload was for pathologies unrelated to the earthquake (28). The USAF SPEARR team commented that their usual mission of providing immediate "resuscitative and stabili(sing)" care [(40), p. 63], was not applicable, due to fewer patients presenting with untreated acute injuries by the time they had arrived. The IDF readjusted staff assignments, unit organisation, and hospitalisation policy, as patients with less urgent medical needs began to present to the hospital (29). Once patients had received treatment, they were transferred to local facilities for ongoing post-operative care—which facilitated patient flow, and sustained delivery of medical aid to disaster victims (29). This process was mirrored aboard the USNS Comfort, who transferred patients to medical facilities run by the GoH and NGOs, for ongoing care (59). By February 28th, the emergency patient load had decreased, and no further patients with earthquake related pathologies remained onboard the USNS Comfort (59). As the medical capabilities of Haitian and NGO managed facilities returned to pre-earthquake capacity, the delivery of care provided, was transitioned to their jurisdiction (9, 59). During the crisis, the healthcare needs of the population encompassed two phases (27). In the first phase—during which, surgical priorities shifted from life to limb saving—surgical capacity was expanded significantly (27). This patient cohort consisted, predominantly, of those with neglected wound infections. The second phase occurred, because of hospital facilities being saturated with patients recovering from their injuries and operative procedures (27). During this phase, clinical space needed to be created, and an increased number of hospital beds was required for longer term patients (27). MSF was able to reinforce provisions for non-earthquake related pathology, by transferring these patients to other facilities (27), in a similar manner to their military counterparts. They also began consolidating medical facilities, following the overall shift in clinical priority, directed by capacity and capability at other NGO and GoH run healthcare institutions (27). It was also noted that several rehabilitative units were established—particularly those that were able provide care to patients with traumatic spinal cord injuries[13] (SCI) (14).

Addressing re-development

Transitioning from disaster response to re-development, was another prominent theme with regards to the disaster response (2, 9, 10, 23, 25, 27, 44, 55, 59). MSF and the IFRC,

13 Contributing organisations included Project Medishare, Healing Hands International, and the Haiti Hospital Appeal—who converted their specialist paediatric facility into an adult centre, with capacity for up to 22 patients (14).

committed substantially to re-development projects (10, 27). Although military actors did not plan to participate in re-development efforts themselves, the Joint Task Force-Haiti (JTF-H) objective—as defined in the OUR mission statement (55)—was to support humanitarian action and provide foundations; from which, the GoH, USAID, and MINUSTAH, could undertake long-term recovery work (44, 55). In light of this, transition planning commenced shortly after the onset of the crisis, with USAID—alongside military augmentation—establishing a "Future Planning Cell" (9). It was noted, however, that there was an ill-defined end point to military operations, and a dearth of strategic guidance with respect to this (9). This, coupled with the GoHs "limited… capacity" [(9), p. 144], lack of consistent financial resources, and legal issues, led to delayed implementation of military handover plans. Finally, regarding the theme of transitional humanitarian activity, numerous stakeholders utilised "cash-for-work" schemes, in a breadth of sectors, to "promote economic and political stability" [(23), p. 31], stimulate reconstruction, and facilitate long-term development. These were largely successful (25), despite reports of issues with establishing guidelines and equitable payment processes, which led to tension amongst the Haitian population and competition between programs (23).

Resources

Within hours of the earthquake, humanitarian aid and disaster response teams around the world began to mobilise. By the day after the earthquake, the UN had committed $10 million US dollars (USD) from its emergency response fund, and the EU committed €3 million euros, with its member states allocating an additional €92 million (16). By mid-February, the UN had requested $1.4 billion USD for the response (16). The United States pledged the largest relief fund it had ever provided for a foreign disaster, spending over $1.1 billion USD. Eventually, private citizens in the US would donate another $1 billion USD (23).

Civilian resources

Despite the massive amounts of funding and supplies sent to Haiti, some UN cluster leads, noted that they had not received sufficient resources. In fact, unequal distribution was a major problem, with some clusters receiving more than they required, and others—especially those clusters relevant to long-term redevelopment[14]—being relatively neglected (25). Furthermore, as disaster events are relatively uncommon, organisations providing disaster relief services are often chronically underfunded and understaffed. The huge mobilisation that had to swiftly take place, overwhelmed some of these groups (19). Additionally, many inexperienced organisations and even individuals, felt compelled to travel to Haiti to offer relief services. While this may have been well-intended, it greatly challenged the humanitarian structure. People arrived who were not self-sufficient, and did not have the proper training or capabilities to enhance the response. Beyond a kind of misguided altruism, there may have been other motivating factors pushing these inexperienced actors into Haiti. Disaster relief activities have high visibility, and provide an opportunity for organisations to increase their credibility to donors, and their ability to compete for funding (43). It is worth noting that this may well have contributed to the influx of relief organisations to Haiti (43).

Despite the massive influx of personnel, equipment, supplies, and money, the response was hindered by an inability to manage what resources were available. In the early days of the response, the ability to deliver materials to the places where they were needed, was lacking. Considerable resources converged in Haiti, but were not necessarily able to get to the points of greatest need (49). The presence of resources alone is insufficient; they must also be accessible and properly used. In the case of the 2010 Haiti earthquake response, some supplies were sent without the relevant equipment, staff, or logistical support to use them. Responders arrived without transportation, or the ability to communicate with affected parties[15], and therefore, their other skills or resources were under-utilised (19).

The initial response often focused on "secure" areas, which left poorer regions with less access to aid. Some of the urban population relocated to rural areas, which, although decreased resource strain in Port-au-Prince, placed increased strain on host communities. This was further aggravated by the lack of humanitarian actors and aid distribution mechanisms in these areas (2), since humanitarian groups tended to base themselves in the capital. In some cases, the distribution of aid itself, caused additional needs; for example, geographic inequities in aid distribution, caused some affected individuals to leave what may have been more stable areas, to access needed relief. This is exemplified by people who moved to camps to access aid centralised there, thereby exposing themselves to increased population density, and its associated risks (1).

Military resources

Multiple branches of the US military responded to the earthquake, under the auspices of the JTF-H (2, 9, 19, 23). JTF-H rapidly deployed personnel and supplies, which was effective in saving lives and reducing suffering—but, came at the cost of efficiency (9). Aspects of the response included civil and public affairs groups, engineers, and medical teams. Military Sealift Command ships, such as the USNS Comfort, are in continuous

14 Such as education and agriculture sectors (25).

15 Many did not speak Haitian Creole or French, and had not included trained interpreters as part of their response teams (19).

operation, and so were able to respond to the disaster swiftly (51). The hospital ship has a 1,000-bed capacity, including 80 ICU beds, in addition to 12 operating rooms, imaging options including a CT scanner, a full laboratory, and an extensive blood bank (61). The Air Force also contributed medical response teams, and although these were less well-resourced than those of the USN, their ability to respond rapidly was commensurate. The USAF SPEARR teams deployed in the first days, attended the disaster with surgical supplies in backpacks, along with one pallet of additional equipment—including a treatment tent and portable generator (40)—and were able to access patients when other, less mobile teams, could not. Despite these early deployments, the overall medical response of the US military was hindered by insufficient medical personnel, staff training, and experience for a response of the magnitude required—as acknowledged in US military reports. There were no medical logistics or regulating officers sent initially, who are critical for ensuring medical supplies and equipment are sourced correctly, and available when needed (9).

Efficiency across the JTF response improved when a working group was established, that held daily discussions on inbound supplies, equipment, and personnel. However, this system was not in place in the early days of the response (9). Overall, the response was limited by its lack of definition. Its role, and therefore the responsibilities and authority of the organisation, was not evident in the early days. Lack of early situational awareness also limited decision making on priorities for the response, making deployment of personnel and equipment more challenging. Forces and supplies entered Haiti in an *ad hoc* manner, not according to formal needs assessments, planning, and distribution procedures (9). Issues with logistics and resource allocation are clearly shown in the example of water. Initially, the capacity to distribute water exceeded what was available. With the arrival of the USS Carl Vinson, a supercarrier that can house thousands, the opposite issue arose. They were able to produce a large amount of portable water, but did not have enough containers to deliver what they were producing (69). Other military teams were noted in military reports to have been assigned tasks, not because they were necessarily the right personnel for the job, but simply because they were already present in-country (47). Even so, the US military's massive influx of manpower and supplies were critical to life saving efforts. At its height, on January 31st, the JTF-H response consisted of 22,000 troops, including 7,000 based on land, with more than 33 ships and 300 aircraft (12).

Needs assessment

Needs assessment in the disaster setting, provides vital information on the overall impact of the crisis, which can then be used to direct relief efforts and ensure efficient use of resources. It encompasses two separate, but related, processes: a rapid assessment used to guide the initial response, and a more comprehensive post-disaster assessment. A rapid needs assessment is critical to make sure responders understand the needs as they stand and develop. In Haiti, it was delayed by negotiations and attempts at consensus-building, rather than fulfilling its greatest mandate: to quickly assess needs so as better to guide the flow of relief. An initial assessment, one of 10 cross-sector surveys costing $3 million USD, did not release its results until February 25th, over a month after the earthquake (14). Additionally, it did not include an assessment of Haitian capacity.

Military actors: Needs assessment

US military actors also conducted their own needs assessments. For example, AFSOC conducted medical site services over 16 sites to assess medical assets (40). Assessors on the ground were able to gather the most useful information on the state of the disaster; however, it takes significantly more time to put these actors in place, and then obtain the information needed to guide the response (70). Therefore, immediately following the earthquake, the extent of damage was unclear. The initial response proceeded without awareness of specific needs, requiring myriad assumptions to be made to commence planning.

Daily assessments were performed by the JTF-H Information Operations team, and this information was provided to the JTF-H commander. Verbal orders were heavily relied on, which led to a lack of an audit trail and hindered force planning and tracking (9). Early difficulties in gaining situational awareness, clouded the determination of requirements and priorities, greatly complicating the delivery and distribution of manpower and supplies. In addition, without a clear needs assessment present, JTF-H adopted a "push" approach—meaning supplies and personnel were sent until the command said to stop (70). Having decided that there was no time to gather complete information about the status of airports and seaports prior to the initial push of relief, and in the absence of coordinated logistics command and control infrastructure, much material was sent to Haiti without detailed plans in place (9). JTF-H were able to supply relief quickly, yet without situational awareness and a needs assessment, these operations were not conducted as efficiently as they may have been. Later, with more resources present, and with improved situational awareness, they transitioned to a "pull" response—requests were made in accordance with needs, leading to increased efficiency and resource flow (70).

Civilian actors: Needs assessment

The difficulties posed by the lack of workable needs assessments, was also keenly felt by civilian humanitarian responders. For example, the small USAID team on the ground initially was quickly overwhelmed, and unable to develop a common operating picture of Haitian medical facilities (13). Data on conditions on the ground, and dissemination of this data—as well as monitoring the quality of aid—are essential for aid targeting and distribution. Although general information pertaining to the disaster was widely available, "detailed ground level information needed for the effective distribution of supplies was lacking" [(13), p. 9]. Many humanitarian actors expended enormous time and effort to amass needs assessment data, but they each developed their own methodologies and tools, making it difficult to aggregate data and gain a comprehensive picture of needs (71). Overall, need and capacity assessments were weak early in the response, and the absence of clear agreement on the parameters of humanitarian need, led to a breakdown in communication with partners—notably the UN and GoH (6). Information management was a major difficulty. Whilst this was meant to be run by the UN's Office for the Coordination of Humanitarian Affairs (OCHA), its small staff and budget, meant that NGOs were depended upon to achieve this, by reporting their findings through the UN's cluster system (19). However, some of these actors were not well trained or highly skilled. It took almost a month for needs assessment to be completed, and by then it was not considered useful, due to delays as well as concerns about methodological flaws (19).

In addition to this, the process was extremely time consuming, with the needs assessment format that some organisations had collectively adopted *a priori*, requiring 3 h to answer all questions, and producing outputs slowly. Results, therefore, took up to several weeks, making some of the results yielded unusable (14, 25). Decisions about donations and goods, were made under great time pressure and with little knowledge about local needs. Additionally, some assessment teams arrived late and "reinforced the... belief that local capacity was too minimal to be included in the international aid response" [(25), p. 23–24]. Overall, needs assessments lacked clear context and analysis of local capacity, and due to this lack of knowledge, "relief efforts and support programs were often unilaterally installed and enforced" [(25), p. 26]—without considering the resources, needs, and desires of Haitian people. Haitian civil society organisations were largely excluded in designing and implementing programs, as the false assumption was made that local capacity was limited prior to the earthquake, and therefore must be non-existent after it (25).

Communication

> "Information management, including in the health sector, appears to be one of the weakest points of response in past disasters. The situation is compounded by the proliferation of general actors as well as agencies addressing highly specific needs." [(14), p. 111]

In any humanitarian response, communication is arguably the most important domain, as all other response domains will fail or succeed, based on communications (72). The destruction included the telephone lines, mobile phone circuits and the electrical grid—which led to oversaturation of limited satellite phones. Furthermore, there was minimal internet access, as the only undersea cable came ashore at Port-au-Prince, and this was significantly damaged (13, 14). Communication is inherently collaborative in nature, and so this section will analyse the interaction between civilian and military actors, during the disaster response.

Civilian and military interaction: Communication

The first issue was language. Most meetings were conducted in English, less frequently in French, and none in Creole (25). Very few of the foreign teams that responded to the disaster were able to communicate in French or Creole (14, 25, 73). Lack of ability to communicate in the language of the affected population, led to confusion about where and when aide distribution would be (25). More and more foreign teams arrived, needing interpreters, particularly for the medical response (39). The US military additionally pointed out the importance of local interpreters, as they also served to educate the responders about the Haitian culture (40).

Information gathering and dissemination, negatively impacted the medical response in Haiti as well. The "ability to pass timely and accurate information was as important as the availability of food and water" [(38), p. 60]. Multiple agencies, including Haiti's *Ministère de la Santé Publique et de la Population*, the Centre for Disease Control and Prevention, and the Pan American Health Organisation, established two systems for surveillance of infectious outbreaks. The data collected into these systems, came from multiple sources, was not standardised, and was of varying degrees of quality—which made interpreting and reporting outbreaks challenging (23).

The relief response in Haiti relied heavily on smart phones and internet for communication. This method of communication was a major issue when attempting to coordinate with the USN and US Coast Guard ships (39, 51)—where these modes of communication are not routinely used. This impacted the effectiveness of the hospital ships. Furthermore, in the context of the USNS Comfort, there was a breakdown in communication about the number and types of patients that it was able to receive, as well as casualty collection point information. Once patients were onboard, there was a delay in establishing how families could get information about their care (74). Additionally, terms utilised, such as "MEDEVAC", had differing meanings between organisations, which created delays and inconsistencies in prioritisation of patient transfer (75). There were four large hospital ships that responded to Haiti, in addition to the USNS Comfort, and all used a different referral system. Each hospital ship did not communicate their admission criteria to each other either. The IDF circumnavigated the issue of medical miscommunication, by designing and implementing their own electronic medical records. As records were backed up on computers, loss of patient information and medical error were minimised (29).

Coordination

Although there is overlap between communication and coordination, the process of coordination is distinct from simply employing effective communication. As one review put it, "coordination requires the existence of a set of principles, rules and decision-making procedures generally accepted by stakeholders" [(16), p. 150]. While these principles are generally well-established within an organisation, the interplay between various stakeholders proved to be the biggest obstacle in coordination of relief efforts in the 2010 Haiti earthquake response. It cannot be understated how the vast number of countries, militaries, and NGOs, responding to the disaster, played a role in the difficulty with coordination (2, 9, 44). This section will focus primarily on the coordination of efforts between civilian and military actors.

Civilian and military interaction: Coordination

Just 11 h after the earthquake, the IDF sent a medical team to conduct a needs assessment and make local contacts for coordination of supplies and where to establish their field hospital. Due to the rapid arrival of the IDF field hospital, they were rapidly inundated with patients, and were forced to serve as a coordinating referral centre for medical teams that were subsequently established in the area. The coordination with local and foreign medical teams was successful in increasing capacity (29, 63, 64). Within 2–3 days, multiple universities and NGOs were in Haiti, and working on coordinating patient flow—including collaborating with the US military to send patients *via* aeromedical evacuation to hospitals outside Port-au-Prince (74). This coordination required establishment of medical liaisons, who would physically travel to facilities to ascertain capacity and capability (28). When the US ships arrived—with intrinsic surgical capability—the field hospitals were, for the most part, well-established. A referral system was set up, so that local providers could send patients for triage to military medical teams ashore—patients were then transported to the ships for complex care (61). The arrival of the USNS Comfort brought with it a high level of surgical and medical capability. While only military surgeons were initially on board, personnel from NGOs were quickly brought in to reinforce capacity to conduct complex reconstruction surgery—which was much easier to accomplish on the hospital ship, vs. the FFHs (76). Military coordination was land based as well as sea based. The USAF set up an EMEDS system, based at Terminal Varreux. This site coordinated with the USNS Comfort to take patients that required long term care, and rehabilitation. They worked with the Haitian Ministry of Health, to coordinate patient movement to local hospitals and NGOs (40). In addition to the US hospital ships, four others arrived from Colombia, France, Mexico and Spain. Each had their own referral system and admission criteria, which led to confusion about coordinating patient movement (14). The IDF, and both US, and Canadian militaries, recognised the importance of appointing liaisons to physically travel between the facilities to coordinate referrals (28, 64). Exemplary coordination continued up until the point of departure, with the IDF ensuring patient hand off to appropriate medical and non-medical facilities (29).

Many NGOs contacted the military medical efforts to volunteer services. Both Project Hope and Operation Smile, had conducted missions with the hospital ship previously. Project Hope had an existing memorandum of understanding (MoU) with the USNS Comfort, which led to rapid integration (51). Go Team, another NGO, also had an MoU in place with USN Southern Command, which also greatly aided integration with the military (51). Operation Smile, faced difficulties in finding who on the military side authorised integration—and put extensive work into trying to support the military, with little success (51).

Pre-existing policy

There were significant delays in response time to the 2010 earthquake, secondary to the pre-existing policy which was in place at that time. In general, previous policy frequently required approvals for resources to be accessed, and the need for these approvals led to delays in mobilisation (72).

Pre-existing policy: Military

Concerning this response, there was a considerable amount of high-level policy, which was either in need of updating or completely non-existent. Within the US military, this was particularly glaring. Only two Humanitarian Assistance and Disaster Relief (HADR) doctrines existed, and the general plan was outdated (13, 44). Within US Southern Command (USSOUTHCOM), the plans that existed, were created for the prior organisational structure, and had not yet been revised to reflect the recent restructuring (70). USSOUTHCOM, the joint military command responsible in the region, was the lowest staffed command in 2010, and its limited personnel led to diminished ability to respond rapidly and effectively (77). No formal guidance existed for the use of USN ships in HADR, and therefore plans in the Haiti response were modelled off casualty care plans, rather than HADR (61). In the initial response, the nearest ships were selected to respond, though this may not have been the best plan of action (78). The Oslo guidelines are frequently cited to help define governance, and they encourage the use of military assets in humanitarian efforts—though UN policy generally is not in favour of such collaboration (6, 13, 43, 79). To that extent, the US military system had policies in place to facilitate participation in the earthquake response, but much of their capabilities are intertwined with various domestic entities. For example, the Patient Movement System was designed for use by military beneficiaries, but is capable of other mission support. However, this requires it to be called upon by the National Disaster Medical System, and to remain under the coordination of US Transportation Command[16] (33).

As the initial response ended, the US military and other actors, needed a protocol for exiting (43). This guidance was not established prior to the earthquake, but is necessary for the military to leave upon mission completion (47). Though rapid deployment is the military's greatest strength, dependency and expectation must be avoided, and because HADR typically leaves little time for policy establishment, it is imperative that this is established beforehand (13).

Pre-existing policy: Civilian

Poor or incomplete policy, contributed to a general lack of preparation for a disaster of this magnitude, a particular disappointment given the presence of the international community in Haiti for many years (9). In Haiti, at the time of the earthquake, was the UN's stabilisation mission—MINUSTAH. However, this was built to maintain law and order rather than to respond to a disaster. Furthermore, their central leadership was affected by the earthquake—significantly impairing their capability as a force (19, 32). Within Haiti, though NGOs such as MSF had taught emergency techniques in local hospitals, limited equipment and supply, led to an inability to practise and adapt these techniques (27). MSF also lacked a pre-formed plan to respond to an emergency of such magnitude (27). Intragovernmental US agencies, such as USAID and the Federal Emergency Management Agency, were also in need of policy improvement to combine their efforts, as their redundancies and lack of leadership contributed to delays (9).

Discussion: Lessons learned

Medical disaster responses have enormous potential to shape the re-development processes that follow. It is essential, that humanitarian practise is guided by evidence, which can be gained through analysing previous relief efforts. The response to the 2010 earthquake in Haiti, remains one of the most complex and expansive humanitarian endeavours to date. Even more unique, was the huge response from military forces. In analysing the data pertaining to each of the priority domains, many "lessons learned" were identified—which should inform future disaster response practise.

16 Another component of the joint military command structure.

The humanitarian response: Lessons learned

The first point to discuss, which was predominantly raised by military actors, is that a clear transition strategy is required from the outset of the crisis response (47, 51). Namely, a timely transfer of the responsibility for medical provision, to the jurisdiction of the host nation and other local and international NGOs. It is essential that this process engages and supports the local government (14) and does not undermine or disempower them, as was seen in Haiti. Following on from this, the local population should be heavily involved in leading the response, and "instead of managing the crisis themselves, international partners should accompany and build the capacity of their counterparts" [(14), p. 141]. This will likely require the sacrifice of short-term efficiency and coordination, while focusing more heavily on strengthening local capacity—which leads to sustained improvements over the long-term. As noted in Haiti, developing medical capacity can be driven by disaster response efforts—which can highlight gaps in medical care that need to be addressed. Following the humanitarian response, the prognosis of patients who suffered SCIs in Haiti drastically improved. This resulted from early international appeals for support, answered by specialists and physiotherapists (14). The influx of specialist resources, as well as an expansion in capability with regard to early supportive care and rehabilitation, meant that those with SCIs had access to a more appropriate level of care (14). The result was that Haitian patients, who previously would have died, now had a significantly improved prognostic outlook (14).

Medical activities must be led by guidelines and local practise. In Haiti, issues arose due to insufficient understanding of "the standards of local care and processes" [(2), p. 64]—meaning that a number of patients received inappropriate procedural interventions, that could not be managed within the local health system. Additionally, any actors who engage in humanitarian relief activities, should ensure that they utilise appropriate clinical governance practises with regard to patient documentation, to enable comprehensive follow up of any disaster victims to whom they provide medical care. Furthermore, they should actively inform themselves of the working practises of the local health system, to safeguard patients from inappropriate surgical treatment that cannot be suitably managed post-operatively.

It is essential that foreign medical teams do not exacerbate the substantial burden already placed on local health systems (80). In Haiti, there were several instances where the actions of the international responders disrupted national capacity, including: the "poaching" [(14), p. 39] of local health professionals, introducing a cholera epidemic (14), and commandeering local health facilities (14). Not only does this behaviour cause excess strain on capacity of the host nations health services, but it risks generating parallel health systems that weaken local infrastructure (81). To combat this, adequately trained personnel should be deployed during the early stages of the response (77, 82). Additionally, if medical infrastructure becomes so stretched that patients require extrication abroad, evacuation options need to be established, including for special patient categories (33). This option should only be a last resort, with preference given to strengthening local capacity. Furthermore, oversight over international patient evacuation, must remain with the national authorities of the host nation (14).

Collaboration between local, international, and military actors, can augment medical capacity during emergency relief efforts (64). This can be facilitated by fostering relationships, either prior to crises occurring—through interagency training and exchange exercises (9, 71); or during emergency efforts—by utilising an integrative FFH framework (64). These FFH units should be prepared to treat a range of pathologies, maintain flexible capabilities that are not tailored according to anticipated activity (64), and be able to support the fluctuating medical requirements of the host nation (63). This will support local health systems, a fundamental requirement when the response must be constantly altered according to the health needs of the host population (14).

Resources: Lessons learned

The affected country's government is best placed to prioritise the flow of resources to reflect changing needs, as the disaster response evolves. As noted by the US military, their approval is an important endorsement, and has the additional benefit of decreasing complaints of favouritism, when this prioritisation is undertaken by a third party. In the face of a massive disaster, this will present a challenge for any government. For low- and middle-income countries, where there is less adequate infrastructure, personnel, and expertise in place—this task may become overwhelming. This suggests a role for an international organisation, to support the affected government in planning and coordinating transport of resources, that is deferred to by the international community in future disaster responses (43). Regional governmental agencies, such as subsidiaries of the UN, are well placed to fulfil this role.

Information is critical for deployment of resources. If the needs of the affected population are not identified and tracked, and the processes governing distribution of resources are inadequate—then knowing what additional resources are needed to effectively source and deploy aid, becomes next to impossible (83). In the early days of the response, logistics mechanisms were overwhelmed by the influx of supplies—some of which contained useless or complicated equipment, that had to be sent back. This wasted time and resources, and limited the space available for arrival of supplies which were acutely necessary. Preparation and planning for the in-country situation is essential. Those with roles in planning and policymaking, must take into consideration that the actual environment, may be significantly different to what is predicted. Information about the current situation on the ground, is essential to ensure that the correct human and material resources are sent to aid the disaster response. In many situations, not all the information will be available in the first hours and days. Forward scout teams may be sent to the affected area to analyse the impact of the disaster. They can provide information on where humanitarian actors may establish themselves, giving consideration to responder safety, and how to set up logistics to maintain self-sufficiency (80). Additionally, in areas that are known to experience frequent disasters, emergency supplies should be stockpiled, so that they may be easily accessed and dispersed in the immediate aftermath of a disaster (51).

Even organisations with extensive experience in Haiti were challenged by the scope of the response, and the unprecedented amounts of donations they received (27). Challenges included: the high financial cost of flying in materials, the bottleneck of the airport, a lack of electricity in hospitals in the early days of the response, a lack of water or food for patients, a lack of local knowledge of reconstructive surgery—due to the lack of equipment necessary to teach these techniques pre-earthquake, a lack of physical therapy, and a lack of psychiatric capabilities[17] (27).

The military has a huge scope of capabilities that can be leveraged during a disaster response, including vertical lift, logistics, communication, and emergency and trauma healthcare. Furthermore, they possess the capability to deploy these assets quickly, in comparison to most civilian organisations (13). While the military can offer very advantageous equipment, whenever possible, locally available resources should be used. This helps to protect the local economy, so that it can continue to function after relief operations conclude (13). In the case of Haiti, the US Navy and Army were better able to capitalise on existing relationships in the region, than its Air Force. This was in part, due to the rotational nature of the Air Force's contractors—who relied on short-term, rather than long-term, partnerships (84).

A successful aid response requires more than good intention or boots on the ground; it requires the presence of people with the skills required to accomplish needed tasks, and the delivery and distribution of the supplies they require to do so. Incorporating adaptability into any team's structure is critical so that, especially early on in a response when there are still

17 At the time, there were only 10 psychiatrists in Haiti to serve the mental health needs of the entire country.

many unknown factors, operations may be adjusted to best provide needed services after arrival (62). This is true of all responders, though is exemplified by medical response teams, who must deliver care in accordance with the pathologies of presenting patients; this will greatly affect the number and type of personnel, supplies, and equipment necessary to run a health facility (62). Flexibility, in terms of both personnel and structure of a field hospital itself, are essential to a team's success. After the situation and its corresponding needs are better understood, priority areas can be identified and subsequently reinforced with additional supplies and staff. This idea of a "resupply", based on actual needs, can be built into policy in the planning phase—as has been reported by IDF planners, who suggest this should occur ideally four to five days after arrival (64). Integrating medical units into the response early on is essential, and training these medical units to provide services in low resource environments, will ensure they can respond—even if the disaster has severely limited the resources available in the early days (52). Military capabilities, as discussed above, can also be advantageous to the medical response: they have medical personnel, equipment, and supplies, as well as the people and equipment to transfer patients and necessary materials (33).

The ability to monitor the number and potential contribution of medical teams in a disaster response is also essential. This requires administrative, financial, and logistical expertise, as well as medical expertise. This was challenged in Haiti, due to the large number of responders without sufficient experience or potential for meaningful contribution, who flooded into the country. Humanitarian medical responders, must also take care that their actions do not further disrupt the functioning and rebuilding of the affected countries. For example, large numbers of Haitian physicians were recruited by humanitarian organisations and offered much higher salaries than what they could earn by staying in Haiti. On a systems level, such actions can further deplete the affected nation's medical institutions and potentially weaken recovery efforts (14).

Needs, post-disaster, change as the response progresses. Immediately after a quake, medical needs are dominated by trauma. Later, medical issues arise that in most cases, could have been treated by the affected area's health system, were its infrastructure not damaged. Finally, infectious disease control, rises in importance. Healthcare relief can be optimised by transferring patients to the facilities where they can be best served. For example, high acuity patients can be sent to tertiary medical structures, while primary facilities can take care of a larger volume of patients with less acute needs. Different medical teams may have access to different personnel, supplies, and equipment. Pooling these resources, and distributing them to where they are most needed, optimises the reach and efficacy of care provided (83). This did occur in some cases during the 2010 earthquake response, for instance, nurses and medics were in short supply and could transfer between groups as necessary (83). The Red Cross also had supplies which were distributed between FFH (83).

In responding to a disaster, especially of the magnitude of the 2010 Haiti earthquake, hospital beds are a finite and precious resource. Maintaining bed availability for urgent treatment must be considered early in the response phase. This may be facilitated by taking discharge planning into account even early on, when bed availability is higher, and by creating temporary, lower acuity centres, where stabilised patients may be housed to free hospital space for those with higher acuity needs (74). Standardisation of record keeping among medical responders, would also be of benefit. Electronic medical records, help improve medical accuracy, by reducing the likelihood of information loss and gaps in continuity of care (29). This holds true in a massive disaster scenario, especially when patients can be transferred to medical teams of different countries, and there is a high amount of provider turnover (29).

Haiti's medical infrastructure was inadequate to its population's needs prior to the earthquake. Responders began treating conditions that had clearly existed *a priori*. While this may have been because the hospital that patients would have presented to had been destroyed in the quake, in some cases humanitarian actors were providing services that had not been previously available. While the humanitarian principle of humanity dictates that "human suffering must be addressed wherever it is found" [(85), p. 2], future responses could benefit from clearer goals at their outset based on the level of pre-disaster infrastructure (22).

People around the world donated to relief efforts in the aftermath of the earthquake—the American Red Cross alone, raised almost $500 million[18] USD (86). This huge upswell of concern and support, however, could have been better leveraged. One suggested method, is to publish information on contacts that NGOs and donors, including private companies and private citizens, must reach out to about donating materials to response efforts (69). Donors may earmark funds for certain initiatives or aspects of relief efforts, in general they are within their rights to do so. However, certain clusters, including those responsible for indispensable redevelopment projects, can end up with comparably less funding (25). It may be beneficial to establish a financial system where some redistribution is permitted between clusters, so that discrepancies between cluster budgets and available funds are minimised (25). When funding is sent to implementing partners, consistent and continued assessment and monitoring, is extremely important to ensure that funds are being used appropriately and efficiently, and that the affected population is receiving the maximum benefit from designated funds (25).

18 It is worth noting that significant amounts of this funding remain unaccounted for, raising concerns that funds were inappropriately managed (86).

Needs assessment: Lessons learned

It is difficult to attain both accuracy and speed, when conducting post-disaster assessments. In this case, rapidity must be valued, and some accuracy neglected to achieve it—initial "rapid" needs assessments must fulfil the dictates of their name, and so speed should prevail over perfection. The aim must be having the right information in time, rather than perfect information too late—although in the case of Haiti, even the latter was not achieved (25). Humanitarian actors must standardise needs assessments. Inconsistencies in methodologies and tools, hamper efforts to build a comprehensive understanding of activities and needs on the ground, leading to the duplication of efforts and wasted resources. Lack of standardisation creates both "too much and too little data" [(71), p. 1107]. By creating better systems for data gathering and sharing, responders can work together more efficiently, and more successfully synthesise their information to prioritise needs and direct resources. Indicators must be chosen and followed by all data gatherers; this latter action was lacking in needs assessments conducted in Haiti. Once obtained, assessments must be followed by decisions that consider existing capacity, observed needs, and practical constraints. Information management is critical, because an excess of unstandardised data, requires inordinate effort to turn into actionable information. The priority is to gather timely information for the purpose of collective strategic planning, and to this end, mutual dedication to an agreed set of standardised indicators is key (14). Open-source information systems, that emerged during this crisis, could be utilised to store the findings of such assessments—enabling all stakeholders to have access to this key resource.

Future responses must rely on improved needs assessments and stronger linkages between the humanitarian community's strategic and operational levels, to target humanitarian assistance more strategically. This could have reduced population movements and avoided additional needs and vulnerabilities, which arose later in the response (6). Importantly, needs assessments should be expanded to better understand context and capacity. Awareness of local capacity is imperative, and should be highlighted in needs assessments and given adequate consideration—otherwise civil society and the desires of the populace, may be ignored (25). Language has been highlighted as one reason for the lack of participation of local NGOs in the cluster system, but as suggested by one report, OCHA should undertake an assessment to better understand why this occurs (25). As per that same report, if context and needs assessments had been done well, "it would have been clear that local capacity was available and... the necessity to integrate... civil society in the response could have been identified" [(25), p. 30]. The post-disaster needs assessment should include information about physical and human damage inflicted by the disaster, financial information on the cost of reconstruction of physical damage, the value of income and services lost because of the disaster, and the impact on the affected population (14). These assessments should be supported by the international community, but should be requested and led by the affected government. In the case of Haiti, a formal request was not made until February 16th (14).

With regards specifically to the medical system, it is known that case mixes encountered by medical relief providers will likely differ based on the type of disaster—for example, more surgical or orthopaedic trauma cases after an earthquake, vs. more medical cases after a famine or typhoon. However, to optimise the response, more complete information about the needs on the ground is still required. From the experiences in Haiti, as well as Nepal, not all of this information is available to the local populace in the hours and days after the incident (80). A rapid needs assessment team, or in the case of the military, a forward scout team, can provide extremely useful insight by travelling to the disaster site and obtaining first-hand information, upon which to base decisions. The military's forward scout teams in particular, are logistically self-sufficient and can perform situational analysis based on disaster impact, time after disaster, and disaster type—as well as pick locations for deployment based on safety, accessibility, and size (80). Some needs are predictable: after reviewing the patient presentations seen aboard USN ships engaged in three earthquake responses, they noted that complex musculoskeletal injuries comprised an overwhelming majority of the disaster-related conditions they saw and treated, which can help future relief missions in determining, if not the supplies and capacities needed for the entirety of the earthquake response, at least those needed for the presentations the USN ships are likely to see (61). Limitations are similarly predictable, the speed with which responders are able to be deployed[19] will be a factor in what cases they can manage, and this must be considered during planning. This idea can be extended to any organisation involved in early disaster response: the required capabilities that were noted in the early days, prior to rapid needs assessment, can be sent initially—with the understanding that improved situational awareness should guide further disbursements of equipment and personnel. Even without a needs assessment to guide action, the conditions under which any field hospital will operate must be anticipated, and planning conducted accordingly. A large number of NGOs are capable of providing basic care, and this need is predictable when responding to a disaster like an earthquake. Fewer organisations are capable of deploying a full-service field hospital, but organisations with this greater medical capacity may learn from the experience of the IDF, by sending

19 For example, large USN ships, such as the USNS Comfort, are limited in how quickly they are able to arrive on-station, and as such, are not a "golden hour" asset. This should be used to further inform the anticipated case load, and the subsequent equipment and capabilities available.

self-sufficient, multidisciplinary teams in the initial response—when even a rapid needs assessment is not complete. This will add significant value to the overall medical response (64).

Communication: Lessons learned

The response to the newly employed open-source information sharing systems, used during the 2010 Haiti Earthquake, was predominantly positive—however, some drawbacks were noted. The chief complaint about the data shared on these platforms, was that there was too much of it, and navigating the data to determine its relevance, was time consuming. This balance of rapidity vs. quality, ended up favouring rapidity. As the search and rescue efforts were relying on quickly translated messages, precision became less important than responsiveness (87). In some circumstances, the sheer volume of responses overwhelmed the crowdsourcing volunteers that worked on translation. For the military, the bandwidth needed to effectively use the internet, was not available on any of the US military ships. Besides the aforementioned overflow, of perhaps irrelevant information, and the bandwidth needed to run social media websites, the open-source sites had potential for misuse and abuse to include cyberattacks (87). This was not an issue in the 2010 response, but in future disasters, these freely open sources may make rescuers vulnerable, as the Global Positioning System (GPS) coordinates will be widely known. Also, in the current landscape, the potential for these sources to be used for spreading disinformation needs to be addressed (38).

Coordination: Lessons learned

The foremost lesson learned, and action plan for future disaster relief operations, was the lack of training. There were internal and external complaints about the US military having a lack of expertise and experience in humanitarian and disaster responses. The UN and NGOs, recognised that they would benefit from cross training with the military as well (26, 47, 51, 78, 88). From these experiences, it was recommended that protocols and priorities should be established between military and civilian actors, and cross training should occur—so that coordination and communication during a disaster would be enhanced (83). Additionally, the US military recognised the need for pre-established plans, and HADR rules of engagement that were scalable (77).

Despite the vast number of medical teams in Haiti, there was not a centralised method of triaging and coordinating patients. That burden fell to the individual field hospitals and hospital ships. One recommendation for future disasters, would be to have centralised triage, managed by the UN's Disaster Assessment and Coordination system, which would ideally optimise resources (63).

It is important to mention that a major contributing factor, to the failure of coordination of relief efforts, is the marketised nature of humanitarian aid (89). The top-down structure of organisations (90), means that ear-marking of projects and "cherry-picking" of causes (91) has resulted in a competitive "market", whereby initiatives are chosen for their visibility—rather than actual merit (89). Money and resources are gathered, but remain as mere capital, rather than being translated into useful areas for development and production (90). It follows, that centralisation emerges as a fundamental aspect of creating a global aid landscape that will seek to address the needs of the affected nations, and avoid "duplication, waste, incompatible goals, and collective inefficiencies" [(89), p. 17]. Furthermore, it is worth noting that the fundamental humanitarian principles of neutrality and impartiality, complicate military engagement during humanitarian response efforts (92). Both issues need to be addressed if additional steps are to be taken towards improving coordination.

Pre-existing policy: Lessons learned

In future disaster responses, it is critical that logistics, staffing, and training standards be established, such that responders can do so appropriately (19). Were it not for previously established relationships, which allowed for deviation from policy, there may have been more substantial issues with the response (9). In the future, the overarching recommendation is that, if the US Department of Defense (DoD) is going to continue to have a role in HADR, they need a dedicated HADR chain of command (9, 43). By creating this, there will be a greater group of commanders, with the skills and training to lead in these situations (9). Because air support is so critical early on for transportation and logistics, a predefined role would be crucial moving forward—as the guidelines in 2010 were thought to be ambiguous (26). No one can debate the US military capabilities regarding command and control, communication, and logistics, as they are unique assets to HADR (43). A concrete and well-defined set of pre-existing policies, supported by a set leadership chain, would enable rapid response.

The influx of large numbers of international actors, has been a recurring theme throughout this study—especially those without the appropriate skills and expertise to be able to meaningfully contribute (11, 14, 19). This was not unique to civilian organisations; it was noted that the extensive US military presence "[hindered] the arrival of aid" [(20), p. 4]—with excessive numbers of non-medical DoD staff having been deployed initially, "[delaying]... medical assets reaching Haiti" [(33), p. 1130]. It is clear that there is a need for improved oversight and governance practises, with regard to organisational participation and conduct in humanitarian relief activities. Current regulation of international organisations, as well as mechanisms for maintaining accountability, are inadequate (93)—this was exacerbated in Haiti, by high levels of corruption (94). Expecting the institutions of the nation affected by crisis, to govern these processes, whilst monitoring the standards of those participating in the response, is unrealistic. International consensus should be reached on guidance and practise, with the aim of increasing standards and quality (25)—and both civilian and military stakeholders should contribute to their development. Once acceptable standards have been developed, the entire international community holds responsibility for safeguarding them. Ultimately, oversight for upholding these standards should remain in the hands of a civilian body. What this responsibility looks like, and to whom it will fall[20], requires further investigation, and importantly sector-wide agreement.

Limitations

The coordination and effort required to conduct research during active humanitarian crises is a significant undertaking. Data collection will always be secondary in the acute disaster event, and the priority of actors, correctly so, is to provide emergency aid to the affected population. This may result in "missing data" when conducting an evaluation, such as this current study. An understanding of the geopolitics and donor influence is required to decipher the agendas of both civilian and military organisations, that engaged in providing assistance. This information is not always readily available or widely publicised, which has implications for the research process, and the narrative of the literature disseminated.

Another limitation, is the large volume of eligible data available for analysis, despite the rigorous exclusion criteria. It is inevitable, even with thorough and systematic reviewing of the data, that some information may not have been captured. Additionally, alterations to practise, made by organisations since the earthquake, may not have been included.

Finally, the most significant limitation, is the lack of inclusion of the Haitian perspective in the available literature. It is essential that future research seeks to include and amplify the academic contributions and expert opinion of Haitian entities.

Conclusion

It is clear, through this review, that the many stakeholders involved had varying opinions and perceptions of the same events. Despite this, the medical disaster response can largely be considered a success.

Future disaster responses must respect the doctrine of national sovereignty, and must not be imposed upon nations in severe distress. International actors must ensure operations are both inclusive, and empowering of host nations, so that they are able to take a leading role in relief efforts. The humanitarian community needs to direct attention towards developing international guidelines, setting a gold-standard for disaster response practises, and regulating the actors involved. Finally, great emphasis must be placed on the importance of fostering strong relationships between humanitarian actors, both civilian and military—which is critical in preventing organisations from "competing, rather than collaborating, to save the most lives" [(1), p. 127].

No modern disaster has yet been as devastating as the 2010 earthquake. Given the ongoing climate crisis, as well as the risks posed by armed conflict (95–98)—this will not remain the case indefinitely. Just as disaster responses influence post-disaster re-development, a nation's pre-disaster capability will influence any disaster response that becomes necessary. Low- and middle-income countries are at greater risk of experiencing natural disasters[21] (100, 101) and the outbreak of armed conflict (102, 103), and simultaneously have health systems and national infrastructure that is less able to withstand the additional burden created by such events (100, 104). In pursuit of health systems strengthening and disaster preparedness, the international civilian and military medical community should seek to form strong and enduring partnerships with those nations most at risk.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

Haiti Disaster Response – Junior Research Collaborative (HDR-JRC)

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Author contributions

MA, MJ, and TW: study design, data analysis, writing, and critical revision. GC: study design, data analysis, and

20 The World Health Organisation seems best placed to fulfil this role, given their experience.

21 Notably, 90% of the Haitian population remain vulnerable to further disaster events (99).

writing. MB, LM, SA, and RH: data analysis and writing. RL, CS, CJ, CH, ER, RG, PJ, SW, TB, and TK: study design and data analysis. NY: data analysis and manuscript revision. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Mental health providers in Ukraine need support but they are not helpless: Professional self-organization and innovative practices

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Introduction

The Russia's military invasion to Ukraine has created a complex humanitarian emergency and the largest refugee crisis in Europe since World War II (WWII) (1). Complex emergencies tend to produce massive and urgent humanitarian and mental health (MH) needs and compromise access to the health care. Response places a heavy burden on local responders who are often members of the same community as the people they serve and are subjected to the same ailments (2). This paper calls for scaling up international support for MH professionals working in war zones and complex political contexts (3).

In this field report author reflects on the experience of remotely responding to a humanitarian crisis in Ukraine to draw preliminary conclusions on prioritized MH needs, available resources, and the barriers to accessing care. Understanding what has gone right may serve as an important lesson for MH providers and humanitarian agencies when planning responses to aiding Ukraine and the future emergencies.

Due to the ongoing armed conflict, verifiable data is scarce, it is hard to get, and many of my references are coming from personal sources, ubiquitous reports by my colleagues, and social media. Therefore, the results must be treated with caution. The situation in Ukraine remains politically complicated, and some responders chose against using their names.

Mental health impact

The war trauma in Ukraine will likely have a long-term, possibly intergenerational MH impact (4, 5). Invasion came as a shock to many and felt like a *betrayal*. Few believed in a real possibility of an attack on the neighboring nation which shares deep historical, cultural, religious, and family ties. Reports about filtration camps, war rape, and kidnapping of Ukrainian children were interpreted as unambiguous evidence of genocidal intent by the Russia's government (6–9). The invasion has been unfolding in real time and has received great *media exposure*. The media attention has attracted the world's sympathy and mobilized worldwide support. Broad use of cell phones and social media has allowed people to stay connected and share vital information as it comes. Such informational overload has also, however, added to the confusion and created difficulty with finding reliable sources.

Based on my observations, providers' reports, and the analysis of the real time communications in the chat groups, the presenting problems have been changing with time. In the immediate aftermath, the most frequent complaints were about shock, disorientation, uncontrollable shaking, difficulties thinking clearly, and disbelief: "It's not real, it cannot be happening."

Many reported symptoms of dissociation, intrusions, flashbacks, crying all the time, sleep problems and nightmares. Often symptoms persisted even after refugees reached a place of safety in neighboring countries. Because of the hypervigilance, people sometimes were refusing sleep medications and fought off falling asleep.

Gastrointestinal (GI) symptoms in refugees (stomach pain, nausea, and uncontrollable vomiting) were so prevalent and severe that, they invoked suspicion of poisoning. However, poison was ruled out by the International Red Cross workers, who suggested interpreting them as a stress reaction (10). GI stress reaction reminded me of the saying "sick to my stomach" which signifies a mixture of fear, repulsion and disgust. A similar expression exists in the Russian language: "*Toshno na dushe,*" "my soul is nauseated." Previously, a strong link between GI symptoms, and trauma and anxiety has been found in war veterans (11), and also cross-culturally (12). For example, Cambodians may experience an "abdominal wind syndrome," a GI syndrome associated with fear of attack (13).

By the end of March, when the reality started sinking in, depression, stresses of resettlement, and worries about the future came to the forefront. People were grieving personal losses, the loss of homes, and life before the war. Mental exhaust, emotional numbness, indifference, and disregard for their own lives, was seen in the refusals to go to shelters or to relocate to a safer place. Some struggled to control anger and rage. Increased irritability and family conflicts undermined family supports at a time when they are most needed. For many, the experience of fleeing and being separated from their family members was extremely traumatic especially when they had to make the decision about leaving behind enlisted men or frail family members.

Many children have witnessed shelling, destruction, and killings; some have been wounded, have lost, or been separated from their parents. Others witness to rape and torture. Parents reported to me and other providers the worsening of the conduct, traumatic attachment problems, and behavioral regression, i.e., acting younger than their age. Usually quiet and obedient children could become either clingy or defiant and act out an uncontrollable rage and anger, physically attacking their parents or peers. Other children presented with emotional detachment: they appeared "eerily quiet and apathetic." There were numerous reports of reoccurrence of enuresis in older boys and girls (personal communications with parents and schoolteachers in Ukraine and Poland).

More recently, psychosocial providers have noticed that somehow people "are getting used to the war," and chronic or preexisting psychological problems such as family discord or problematic drinking have started to (re)surface (personal communication).

As it often happens during humanitarian crises, persons with special needs are especially vulnerable (14). They have fewer supports and encounter additional barriers to accessing already scarce resources.

Even with the extensive help of volunteers, the elderly, chronically ill, or persons with physical or mental special needs often were unable to relocate, access the health care, medications, and meet other basic needs. Some stayed behind because they were afraid to leave their familiar surroundings or did not want to be a burden to their family. They were not able to receive lifesaving medical treatment and have been suffering and dying of preventable causes.

Strength and resilience

Russia's aggression has left citizens of Ukraine shocked and traumatized. It has also highlighted their resilience and strengthened national cohesion. Many named family, cultural values, faith, and their love for Ukraine as main sources of strength and inspiration for perseverance.

The *memories of surviving* WWII have been helping Ukrainians to survive the current war: elders, for example, have been teaching younger generations how to recognize the sounds of shelling, how to know when the danger is over, and where to find the safest places to hide.

In recent decades Ukraine has accumulated many well-trained MH professionals and crisis workers. A *widespread psychoeducation* increased the public's awareness of MH needs, educated about psychological trauma, and sensitized the public to recognizing trauma reactions. It helped raise awareness and destigmatize MH issues and formed a demand for trauma services.

In Ukraine, *the spirit of volunteering* has run exceptionally strong. Sometimes risking their own lives, volunteers have been checking on those in need, delivering food and medications. After relocation, refugees have immediately started volunteering themselves and sharing their resources. Many of those who earlier fled Belarus and Russia to escape political persecution have been helping with transportation and language services, babysitting, and connecting with health care.

Professional self-organization

The initial MH response was marked by frantic and at times chaotic efforts by overworked MH responders to meet as many needs as possible. But only 2 months later, we saw an entirely different landscape in MH services provision. Although the systems of psychosocial support still face challenges, the professional community in Ukraine was able to come together in a very short time, overcome their differences, self-organize, and take charge in coordinating MH response, requesting specialized training and professional assistance when needed.

MH and psychosocial support providers in Ukraine, often traumatized and lacking safety themselves, have stepped in to provide psychological support and psychoeducation about coping with extreme stress and severe trauma. They have been bearing witness, advocating for the needs of the people they serve, and raising their voices against the war. The overall response to this humanitarian crisis has demonstrated the strong commitment of Ukrainian MH providers to their professional mission. This self-determination and the capacity to self-organize in response to pressing humanitarian needs indicates the maturation of a helping profession and helps to cement its role as an integral part of society.

Barriers to accessing care

A tremendous amount of work has been done, and a lot has been accomplished, but many barriers remain. Finding bilingual resources has been a sensitive issue. Although the Russian language is commonly spoken in Ukraine, the war has understandably made a trigger for some Ukrainians.

Despite the widespread use of social media, many have not been aware of the available psychosocial resources or how to access them; vital information is spread mostly by word of mouth.

Ukrainian health and MH care systems had been functioning well-before the war. These systems were able to cushion most needs, but the availability of facilities, medications and logistics were compromised by the war.

Services offering has remained fragmented. Fragmentation in is an affliction that has traditionally hindered the effectiveness of humanitarian response. It adds to confusion, makes it difficult to navigate the system, and reduces efficiency in accessing scarce resources (15).

Innovative practices: Telemedicine, helping chat groups, chatbots

Telemedicine

Emerging technologies have transformed MH response to this emergency.

Accelerated digitalization of services during the COVID-19 pandemic has provided an unexpected advantage and expanded the access to MH practice and education. Telemedicine has allowed providing MH services remotely to communities that are otherwise difficult to reach, that are dispersed, or where it may not be safe to travel.

Chat groups

Immediately after the invasion, the biggest challenge was connecting those in need with the providers. Almost instantaneously, existing virtual chats and support groups started accommodating requests from Ukraine and new ones started emerging on Telegram and Facebook. They aimed at real-time matching of on-site needs with local and remote resources. In these designated channels, anyone with war-related MH problems could post about their urgent needs, and self-appointed MH providers from different backgrounds – and often residing in different countries – would respond to these inquiries in real time.

The 2020 political crisis in Belarus led to the emergence of self-managed self-help chat groups. They have continued offering their capacity, MH resources, and the services to Ukrainians in need (e.g., https://www.facebook.com/groups/myrazam.info/). This model has proven itself useful in the aftermath of the invasion in Ukraine. Examples include: СвітлоЧат – Психологічна допомога українцям під час війни (Psychological help to Ukrainians during the time of war. Owner A. Pozhydayev), and Психологическая помощь Украина (Psychological assistance to Ukraine.).

As per owners' reports, at various times, these chat groups employed between 400 and 900 professional Ukrainian and Russian-speaking MH professionals from all around the world, but mostly from Ukraine. They responded to more than 40,000 inquiries. During busy days, they were receiving up to 1,000 inquiries, and currently receive about 200–300 requests a day.[1] These chats were also used to share information about psychosocial resources and to provide peer support.

Chatbots in Ukrainian, Russian, and Belorussian languages are yet another innovative practice that is an example of growing transnational professional projects. For example, chatbots Faino (https://t.me/faino_psy_bot\relax$\@@underline\hbox{/}\mathsurround\z@$\relax) and GotoHelp (https://gotohelp.eu/). Although promising, further research into these innovative practices is needed before recommending their broader implementation.

Conclusions and recommendations

Absent centralized guidance and often traumatized and unsafe themselves MH professionals in Ukraine have assumed responsibility for the psychological well-being of the community. In addition to providing care for the victims of

1 At the time when this paper was written.

atrocities, they have taken a lead in organizing community support and have become an inspiration and a driving force in shaping community resilience and recovery.

The response in Ukraine has demonstrated that public awareness of the psychological effects of trauma has strengthened community resilience and significantly reduced stigma of reaching out for MH help.

Lessons from this response underscored the importance of increasing trauma and Psychological First Aid competencies for MH and psychosocial providers, teachers, health care workers, and volunteers.

Many who most need aid will not reach out (14). The community outreach is needed to engage in services those who are least mobile, most vulnerable, severely traumatized, or depressed. Prioritizing the development of outreach workforce and the community-based support systems is essential.

The presence of the advanced health care systems and well-trained medical and MH cadres in Ukraine created unexpected challenge for humanitarian medical and psychosocial aid agencies. It highlighted the shortcomings of the traditional giving-receiving model based on the inherently in-built power differential (15). New models of psychosocial supports are needed. These models should be based on establishing equal partnerships and collaboration between foreign and Ukrainian professionals.

International professional community shall prioritize supporting local MH providers, which includes funding and technical support. In the spirit of humanitarian accountability, it is important that determination of the priorities, scope and scale of relief efforts is established in closed consultation with local providers who are to lead the response (15). The validity of the preconceived assumptions and approaches to crisis response and trauma treatment derived in a different context and culture must be carefully re-evaluated.

It is never too early to think about the future, even while war rages on. Although wars don't last forever, they do manage to sever communal, family, and professional ties. When the world is divided, MH professionals can play a key role in reminding both sides about humanitarian values, compassion, and caring—essential to building a peaceful future. Only then is there hope for a violence-free future.

Author contributions

The author confirms being the sole contributor of this work and has approved it for publication.

Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The viewpoints of residents of Kerman, Iran regarding the challenges and barriers of preparing households against earthquakes: A theory-guided qualitative content analysis

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Introduction: Earthquakes cause a lot of damage and casualties. For various reasons, most households are not prepared for earthquakes. This study aims to identify the challenges and barriers to households' preparedness against earthquakes from the viewpoint of Kerman residents.

Methods: This qualitative-directed content analysis study was conducted from December 2021 to May 2022 in the city of Kerman in southeast Iran. Data was collected by purposive sampling through in-depth and semi-structured individual face-to-face interviews with 48 households.

Results: After multiple rounds of analyzing and summarizing the data based on the social-cognitive theory and taking into consideration similarities and differences, five main categories and 19 subcategories created based on the results of data analysis and including (1) Challenges related to cognitive factors (2) Challenges related to behavioral factors (3) Challenges related to the physical environment (4) Challenges related to the social environment and (5) Challenges related to financial factors.

Conclusion: Although the participants listed many challenges and barriers in different fields, in order to overcome the barriers and challenges of preparing households for an earthquake, the support of the authorities and the cooperation of the residents are necessary.

KEYWORDS

earthquakes, family, risk reduction behavior, psychological theory, barriers

Introduction

Earthquakes cause extensive damage to homes, businesses, and infrastructure, as well as casualties and financial losses (1). As the World Health Organization (WHO) reported, over the past century alone, 1,150 fatal earthquakes have happened in 75 countries worldwide (2). Earthquakes annually cause more than 10,000 deaths, most of which occur in developing countries (3). Iran is one of the most seismic regions in the world, and many destructive earthquakes have occurred in this country (2). About 93% of regions in Iran are at risk of earthquakes. More than 70% of Iran's big cities are located near active faults (4). Iran has experienced 18 earthquakes of over seven Richter magnitudes in the past 90 years, causing severe socioeconomic damage and killing thousands (3). In Kerman province alone, more than 40,000 people have died from earthquakes in recent years (5).

Disaster risk reduction management consists of three phases. Prevention, mitigation, and preparation are in the phase before the occurrence of a hazard; response and emergency relief are in the phase during the occurrence of a hazard; and recovery (reconstruction and rehabilitation) is in the phase after the hazard (6). Acquiring knowledge, skills, planning, and storing emergency equipment and supplies are essential measures in the preparation phase (7). According to studies, most households are not prepared for hazards (8–11). Preparedness against hazards is affected by various factors, including demographic, behavioral, environmental, social, cognitive, economic, physical, and cultural factors (7, 8, 11–14). From the point of view point of the social cognitive theory, neither individual factors nor environmental stimuli alone can affect a person's behavior. One of the essential features of this theory is the combination of social structures with personal dimensions (15).

Studies in different parts of the world have shown that perceived challenges and barriers significantly reduce preventive measures and disaster preparedness (10, 16–19). In a study by Najafi et al., conducted after the Kermanshah earthquake, earthquake victims commented on the necessities and challenges of earthquake preparedness in various fields (20).

Considering that the present research is a part of an exploratory sequential study, it was necessary to identify the opinions and beliefs of people about the barriers and challenges of households' preparedness against earthquakes for formulating items and designing tools. From the viewpoint of Kerman residents, since Kerman province is one of the earthquake-prone regions of Iran and most of the people in this region have experienced earthquakes, this study aims to identify the challenges and barriers to households' preparedness against earthquakes.

Methods

Study design

A qualitative study was conducted from December 2021 to May 2022 as part of more extensive research on the design and validation of a tool for determining the factors influencing households' preparedness behaviors for earthquakes based on the social-cognitive theory. This study was conducted using a directed content analysis approach. When there is a theory or research about a phenomenon, but it is not complete and more descriptions should be made about it, the researcher uses a directed content analysis approach (21). Pre-existing theory can help to design interview questions.

Study population, participant selection, and data collection

The research population was the households of Kerman city. The participants were selected using a purposive sampling method and with maximum diversity in terms of gender, age, education, occupation, region of residence, experience or lack of experience of destructive earthquakes, and the presence of vulnerable groups at home. Samples were selected from four health centers in different parts of Kerman city. Participants were selected with the cooperation of healthcare workers. First, the health workers contacted the heads of households, and after stating the research objectives, they obtained their consent to participate in the interview. Then the researcher was introduced to the participants. Because the responsibility of preventive measures and preparation against earthquakes rests with the father or mother of the family, one of them participated in the interview at their own discretion. Before the interview, the purpose of the interview was explained. The participants were assured that their information would be recorded confidentially and anonymously.

Data was collected through in-depth individual semi-structured interviews. All interviews were conducted face-to-face. The participants themselves decided the time and place of the interview. The interview was conducted with open and predetermined questions. The questions about the obstacles and challenges of households' preparedness against earthquakes were based on Bandura's social-cognitive theory constructs. Before the interview started, the study's objectives were explained. Participants were assured that their participation in the study was voluntary and that the information would remain confidential. Informed consent was obtained from all participants for the interview and audio recording. Before the interview, a brief explanation of the concept of cognitive, behavioral, and environmental factors was given to the participants. For example, it was explained to them that the barriers of the physical environment include problems related to the building, the items inside the building, the furniture, the neighborhood environment, etc. The obstacles and challenges of the social environment, including the problems that the members of society have in their relationships with each other, or the obstacles that are related to the interaction between people and groups, institutions, or government organizations, each of these obstacles can affect their readiness to play a role in earthquakes.

TABLE 1 Open-ended questions.

Factors	Questions
Cognitive barriers and challenges	1- What barriers or challenges exist to increasing households' knowledge to prepare against earthquakes? 2- What false beliefs do people have that make them not take action to prepare against an earthquake? 3- What are the negative consequences of preparing for earthquakes that causes households not ready for it? 4- What beliefs do people have about their abilities that barrier earthquake preparedness measures?
Behavioral barriers and challenges	1- What inappropriate and wrong behaviors are there among the people before, during and after the earthquake?
Environmental barriers and challenges	1- What are the barriers and challenges in the physical environment that affect the preparedness of families against earthquakes? 2- What are the barriers and challenges in the social environment that affect the preparedness of families against earthquakes?

Each interview began with an open question, and during the interviews, exploratory questions such as "What do you mean by this?" or "Could you please explain more?" were used. The interview questions are presented in Table 1. Data saturation was achieved after 48 interviews. After interviewing 46 households, the researcher came to the conclusion that saturation had been achieved and stopped sampling after conducting two more interviews to ensure that no new data was obtained. Due to the disagreement of 12 participants with recording interviews, note-taking was used instead of recording for those 12 samples. Interviews lasted between 35 and 60 min.

Inclusion and exclusion criteria

Willingness to participate in the research, having time, and spending the necessary time interviewing were included. The father or mother of the family, whoever was more inclined to participate or could provide more information, was interviewed. Households that did not have points to express or did not want to be interviewed, and households where the couple's age was <18 years old were excluded.

Analysis and presentation

Data analysis was performed according to the steps proposed by Hsieh and Shannon (21). Data analysis was done simultaneously with data collection. The data was analyzed using the directed content analysis method. According to this approach, the key concepts of social-cognitive theory were considered as the first category. Then practical definitions for each category were determined using the structures of this theory. First, the content of the recorded or noted interviews was typed verbatim. The text was reviewed several times to find content that matched the predefined categories. Sentences and phrases were considered as meaning units. Coding of the interview text was done based on pre-specified features, and the codes were placed in the identified categories based on conceptual similarity. Categories and subcategories were formed depending on the scope and logical relationships of the data. Also, the codes that did not correspond to the initial predefined categories were defined as new categories.

Data accuracy and robustness

This study employed strategies recommended by Lincoln and Guba for assuring trustworthiness (22). To obtain credibility, the researcher had sufficient and appropriate interaction with the participants and gained their trust to collect information. Moreover, sufficient time was allocated for data collection and analysis (6 months). Also, the participants from several health centers were selected with maximum variety. Peer-check strategies assess the dependability of data. Peer-check was performed monthly to ensure that the research team had a thorough discussion about the data. Also, member-checking by two participants and rectifying the codes that did not accurately describe the participants' point of view (based on their own opinion) improved dependability. To improve the confirmability, the supervisor and advising professor reviewed some quotations, codes, and extracted categories and confirmed the accuracy of the coding process. For data transferability, the study results were given to several people who had the same characteristics as the project participants, but did not participate in the study (external check), and they were asked to state whether they agreed with the project results.

Results

A total of 48 interviews were conducted with 48 participants (21 men and 27 women). The average age of the participants was 42 years. The average size of the household was about four people. Nine households lived in a rented house. Twenty-four households lived in apartments. Forty-two participants had academic education. There was a vulnerable person in 37 households. Five hundred and six codes were identified without calculating the overlaps. After multiple rounds of analyzing and summarizing the data based on the social-cognitive theory and taking into consideration similarities and differences, five main categories and 19 subcategories created based on the results of data analysis. Main categories including (A) Challenges related to cognitive factors (B) Challenges related to behavioral

TABLE 2 Categories, subcategories, and codes about preparing households against earthquakes based on Bandura's social cognitive theory.

Categories	Subcategories	Example of the codes
Challenges related to cognitive factors	Lack of Knowledge	Impossibility of using educational materials (low literacy, illiteracy, old age)
		Reluctance to participate in training
		Lack of attractiveness of training
		Inadequacy of training
		Lack of time to attend training
		Lack of access to face-to-face and practical training
		The information propagated by social networks might be misleading.
	False Beliefs	Fatalism
		Misconceptions about the origin of earthquakes
		Believing that if they think too much about earthquakes, it will happen.
	Self-efficacy	Lack of belief in their ability to use tools and equipment
		Lack of belief in their ability to maintain calmness and appropriate behavior during an earthquake
		Lack of belief in their ability to learn and use the training
		Lack of belief in their ability to help others during an earthquake
	Negative outcome expectations	Having fear and stress during training and exercise
		Thinking that children have lack of understanding about preparation and drills and there is a possibility of psychological and physical harm to them
		The possibility of causing physical and mental injuries in the elderly, disabled and pregnant women due to movement restrictions and stress during exercise
Challenges related to behavioral factors	Lack of skills	Lack of skills in the correct arrangement of home furniture
		Lack of fire extinguishing skills at home
		Lack of first aid skills and ability to resuscitate patients
		Lack of skill in cutting off electricity and gas
		Lack of skill search and rescue
	Behavioral challenges before the earthquake	Failure to observe safety precautions
		Placing additional items in the staircase
		Placing the pot on the edge of the balcony
		Blockage of the route due to improper parking
	Behavioral challenges during the earthquake	Inappropriate behavior during the earthquake (unthoughfulness, confusion, etc.)
		Calling emergency services for trivial issues, which delays providing services to people in need.
	Behavioral challenges after the earthquake	Ignoring mild earthquakes and resting in an unsafe place
		Failure to observe safety precautions in the tent during emergency accommodation
		Creating traffic on the streets
		Emotional behavior and unnecessary travel to the affected area
Challenges related to the physical environment	Building (structural factors)	The impossibility of reducing structural vulnerability in rented houses
		Buildings are not resistant
		Building non-standard and illegal houses on the outskirts of the city
		Failure to observe engineering principles in construction
	Furniture and appliances (non-structural factors)	The impossibility of reducing non-structural vulnerability in rented houses
		Lack of securing home appliances such as shelves, chandeliers, etc.
		Worn out non-standard home appliances such as oven, stove, water heater, heater, etc.
		The house is not safe due to improper wiring and plumbing, etc.
		Improper arrangement of home appliances and furniture
		Lack of emergency stairs in most buildings
	Emergency equipment	Lack of emergency accommodation supplies such as tents, etc. (Failure to evacuate the house)
		Lack of access to special equipment for the disabled
		Lack of essential manual rubble collection equipment
		Insufficient home equipment and supplies, such as first aid box, etc.

(Continued)

TABLE 2 (Continued)

Categories	Subcategories	Example of the codes
	Physical texture of the neighborhood	Buildings in the neighborhood lack resistance
		The narrowness of the passages
		Apartment living and high population density
	Infrastructure	Lack of access to essential services and equipment in some areas
		Electricity, gas, and telephone were cut off during the earthquake.
	Weather factors	Emergency accommodation is impossible due to cold weather and rainfall. As a result of failing to evacuate the house at the time of the earthquake
		The possibility of secondary hazards due to the use of cold season heating machines
Challenges related to the social environment	Security	Failure to evacuate home due to insecurity and possibility of robbery from home
		Failure to observe others' privacy during emergency resettlement
		Failure to consider a suitable and secure place for emergency evacuation
	Communications	Inadequate communication with relatives, neighbors, etc., due to lifestyle
		Inadequate communication between family members
		Social isolation of vulnerable groups (elderly, disabled, etc.)
	Participation	Non-participation of residents for preventive measures and neighborhood preparation
		The discouragement of the residents due to the non-cooperation of some members of the neighborhood
		It is less possible to participate in neighborhood events in big cities.
Challenges related to financial factors	Financial resources	High cost of livelihood and lack of funding for preventive measures and preparations
		High cost of retrofitting buildings
		The expensive cost of renting safe houses
	Insurance	Lack of importance of building insurance
		Lack of financial power to pay insurance

factors (C) Challenges related to the physical environment (D) Challenges related to the social environment and (E) Challenges related to financial factors shows in Table 2.

Challenges related to cognitive factors

Lack of knowledge

The participants stated that acquiring knowledge can effectively improve households' preparedness behavior and reduce losses and casualties, but for various reasons, most people's awareness is not enough or is incorrect. For example, A 34-year-old bachelor's degree woman said:

> I *am an employee, and when I come home in the evening, I am busy with housework. I have to take care of my husband and children. I don't have time to participate in Red Crescent classes "(P13).*

False beliefs

Participants stated that some people have false beliefs, which lead them to not take preventive and risk reduction measures and feel weak against hazards. A 45-year-old bachelor's degree man who had experienced the Bam earthquake said:

> *"Some people think that an earthquake is God's punishment and we can't do anything. Were the children killed in the Bam earthquake because of God's anger? What did they do? The children were innocent. You have to inform the people"* (p5).

Self-efficacy

Some participants mentioned that they thought they could not take preventive measures and prepare and behave efficiently when an earthquake occurs. A 52-year-old master's degree woman said:

> *"I get a lot of stress during an earthquake. I'm not sure if one day there will be a strong earthquake in Kerman, I will be able to keep my calm" (P4).*

Some people stated that they do not have the necessary skills to prevent secondary hazards and reduce harm.

A 43-year-old diploma woman said:

> *I haven't been trained because I don't think I can help the wounded. If I see someone injured, I feel bad. Someone who chooses to do this must be very brave. I really don't have any skills" (P25).*

Negative outcome expectations

The participants commented that they thought preparing for earthquakes and doing drills at home might harm vulnerable groups' physical and psychological health.

A 37-year-old woman who had a seminary education said:

> *"I have three small children. They may not understand why I am preparing a rescue kit, and it scares them because they think something is going to happen" (P1).*

A 34-year-old master's degree man said:

> *"My wife is pregnant; I know she can't move fast. If we try to drill at home, she may fall and get more injured, or she may get stressed, and her blood pressure will rise. We prefer not to drill while my wife is in this condition "(P15).*

Challenges related to behavioral factors

Lack of skills

Some participants mentioned that after the devastating Bam and Zarand earthquakes, they had to search for and save their loved ones themselves in the early hours before the rescuers were present. They mentioned that they had no training and did not know how to save an injured person. A 50-year-old bachelor's degree man said:

> *"In the Bam earthquake, the whole city was completely destroyed, and there was not enough relief force. We had to pull the families out from under the rubble. People did not know how to save a wounded person. Later, I heard that many of the wounded were paralyzed because we did not know what to do. Everyone, in my opinion, should learn these skills before the earthquake"(p11).*

Behavioral challenges before the earthquake

Participants said that some people's inappropriate behavior causes others to get hurt during an earthquake. A 43-year-old master's degree woman said:

> *"When you look at our building, you see that they put flowerpots and other things on the balcony without any protection, so if there is an earthquake, they will fall on people's heads. I wish someone would warn them that this is dangerous" (p33).*

Behavioral challenges during the earthquake

Excessive emotional or unthoughtful behavior is one of the challenges during earthquakes that participants mentioned. A 35-year-old master's degree man said:

> *"Many people get fearful and confused. For example, my sister is terrified of earthquakes and does things that are not appropriate at all. When she is so afraid, her children get afraid as well "(P16).*

Another challenge that participants said was that some people crowd medical centers for minor injuries that do not require hospital visits.

A 41-year-old bachelor's degree woman who worked in a hospital said:

> *"During an earthquake, even with minor injuries that do not require immediate treatment, people call the emergency medical center or go to hospitals, which may cause acute cases to receive delayed medical services" (p43).*

Behavioral challenges after the earthquake

Participants commented that many secondary hazards and challenges after an earthquake can be prevented by preventing emotional and hasty behaviors and following safety tips. A 39-year-old master's degree man said:

> *"After the earthquake, people come to the street by car, and there is a lot of traffic in the city. I think they should be taught in advance not to have these behaviors "(P18).*

A 48-year-old master's degree woman who had experienced the destructive Bam earthquake said

> *After the destruction of Bam city in 2003, many people from far and near cities entered Bam city. Iranians are very altruistic and like to help victims in this situation, but they don't know that this behavior will cause congestion in the city and cause more problems (p14).*

Challenges related to physical environment

Building (structural factors)

Participants stated that unsafe and non-resistant buildings are among the most challenging.

A 50-year-old diploma man said:

> *"In my father's village (*Dahuiyeh*), although the houses were newly built, after the earthquake, 90% of the houses were destroyed, and a large number of people in the village were killed. Because the houses were not built according to engineering principles and standards" (p20).*

Equipment (non-structural factors)

Participants commented that equipment inside buildings can result in death or injury if it falls, breaks, or blocks exit routes.

A 44-year-old physician woman said:

> *As a tenant, I can't do many things, I can't even hammer a nail into the wall. The owner of the house may not agree that I fix the shelf so that it doesn't fall down during an earthquake* (P2).

A 43-year-old diploma woman said:

> *"Today's houses are very small; we don't have enough space for furniture. We have to put cupboards and shelves in the hall and put many things inside. If an earthquake happens, even if the house is not damaged, these utensils will cause problems for us" (P25).*

Emergency equipment

As some participants commented, appropriate equipment was not available to rescue people. A 50-year-old diploma man, who was severely injured in the Zarand earthquake, said:

> *"I was under the rubble for several hours. I could not move. People did not have shovels and picks, and they could not save me. If they had pulled me out from under the rubble earlier. God helped me to survive, but it took me some time to recover" (P20).*

The participants who experienced the Bam earthquake also stated that one of the main problems in the early hours after the earthquake was the lack of manual debris removal equipment. They believed this equipment should be prepared in advance.

The physical texture of the neighborhood

Participants commented that the considerable distance between the houses and the evacuation place, the lack of strength of the buildings in the neighborhood, the density of the buildings, and the insufficient width of the routes could cause many casualties and injuries during an earthquake.

A 48-year-old master's degree woman said:

> *"Take a look at our neighborhood and you will notice that the houses are old and dilapidated. The alleys are narrow. If a strong earthquake happens, the houses will crash into each other and the alleys will be closed. My friend said that when I went to Bam after the earthquake, I could not find my father's house because the houses were crashing on each other. Several thousand people died in Bam because they could not save people quickly" (P8).*

Infrastructure

Participants commented that poor infrastructure, lack of access to facilities in some areas, and disruption of communication systems during an earthquake are critical challenges.

A 46-year-old bachelor's degree woman said:

> *"When there is an earthquake here, sometimes the phones are cut off. My daughter, who is studying at a university in another city, gets very worried about us if she can't talk to me. The authorities should solve the telecommunications problems. If there is an earthquake, the phones will be cut off, and this causes people to worry because they cannot call [their family members] "(P37).*

Weather factors

Many participants said that cold weather and rain are significant barriers to an emergency evacuation.

A 41-year-old bachelor's degree woman said:

> *"I remember in 2018 or 2019, there were many earthquakes in Kerman, and the weather was cold. Where should we go if we wanted to stay out of our buildings? Has the government considered a place where people could take refuge during an earthquake? We cannot sleep in the park or on the street in winter. Our children get sick "(P31).*

Challenges related to the social environment

Security

Participants mentioned that one of the most critical issues during an earthquake is people's security.

A 51-year-old bachelor's degree man said:

> *"During an earthquake, people are afraid of their houses being robbed. That is why they prefer to stay in their dilapidated houses and do not leave the houses to go to a secure place" (P3).*

A 60-year-old primary education woman said:

> *"My husband is dead and I don't have a son. If there is an earthquake and we want to leave our house, I can't go and sleep in a park with two daughters. I don't dare. We may be persecuted" (P47).*

Communications

Participants mentioned that more communication between family members, relatives, and neighbors can increase mental preparedness, and knowledge sharing. Insufficient social communication was mentioned by several participants.

A 52-year-old master's degree woman said:

> *"People are very busy. They have less time to visit each other. I don't see my relatives often because they live in another city. Also, since I am an employee, I rarely see my neighbors. I think that if we have a lot of communication with each other, we will be aware of each other's problems and we can help each other to solve them. We can also learn a lot from each other about earthquake prevention and preparedness" (P4).*

Participation

The participants mentioned the insufficient collaboration of the neighborhood residents in the fields of preventive measures, reduction of damage, and improvement of preparedness as one of the main challenges for earthquake preparedness.

A 50-year-old bachelor's degree man said:

> *"We have been living in this neighborhood for a year. We don't know our neighbors, and everyone is busy with their lives. I remember when there was an earthquake in the area around Zarand. We were living there. During the earthquake, the wall of one of the neighbors got many cracks. We talked to the neighbors and repaired the wall. Because it may fall on the street and harm the people passing by" (P29).*

Challenges related to financial factors

Financial problems

One of the barriers most participants mentioned was financial difficulties. A 51-year-old diploma man said:

> *"Now, the cost of living in Iran is very high. Our income is also very low. We can't even buy a smartphone for our children so that they can study during this Corona situation. I think we should let's spend our money on more important things, not on an earthquake that might not happen at all"* (P23).

A 32-year-old diploma man said

> *"My house is made of clay and mud. I know how dangerous it is to live in this house. But I have no choice, I have to live in this house. Because building a durable house requires a lot of money, which I don't have" (p24).*

Insurance

One of the barriers most participants mentioned was insurance problems.

A 40-year-old bachelor's degree man said:

> *"Because people do not have enough income, they do not pay much attention to insuring their houses, and if an earthquake happens, in addition to putting their lives in danger, they also lose a lot financially" (P42).*

Discussion

This research was conducted to identify the challenges and barriers to households' preparedness against earthquakes from the viewpoint of the residents of Kerman. The analysis of the participant's viewpoints showed many challenges and barriers to preventive measures and the preparation of households against earthquakes. Based on socio-cognitive theory, challenges and barriers were categorized into cognitive, behavioral, and environmental (physical, social, and financial) factors.

Challenges related to cognitive factors

For various reasons, most participants believed that most households lack sufficient knowledge regarding earthquake preparedness measures. In Najafi et al.'s study (2018), which interviewed 132 heads of households living in Tehran, lack of knowledge and insufficient time were identified as the most important barriers to earthquake preparedness (18). A review study showed that Iranians with a higher knowledge level had a better performance in preparing for an earthquake (23). In Appleby et al.'s study in Romania and Malta (2021), most participants were unaware of disaster preparedness guidelines, and those with more knowledge reported greater preparedness (24). According to Yu et al.'s study in China (2020), people with a higher knowledge level had more disaster preparedness behavior (25). Considering that lack of awareness is one of the most important reasons for inadequate preparation for earthquakes, various educational programs should be designed and implemented considering the audience's conditions to improve households' preparedness behavior.

Some of the participants said that people around them believe that adverse events such as earthquakes are controlled by external factors and that humans have no authority over or ability to overcome them. Some participants did not agree with this. These beliefs are considered barriers to health-related behaviors. In a study by Askarizadeh et al. in Tehran, decision-making about risk reduction behaviors decreased with increasing sources of external control (26). According to a study by Chen et al. in China (2019), households with less determinism were more likely to adopt emergency preparedness behaviors (27). In Armas et al.'s study in Romania (2018), people with a belief in an external locus of control had high stress and more worry about hazards, and felt less prepared (28). According to a study conducted in Saudi Arabia (2016), contrary to expectations, households with a higher level of attributing earthquakes to supernatural factors were more prepared for earthquakes. The authors stated that in Muslim societies, based on hadiths and the Qur'an, people may believe that they are obligated to protect their lives from dangers and that any disaster they face results from their behavior (29). Perhaps due to the unpredictability of an earthquake's exact time and place, people may think they have less control over earthquakes and show less preparedness.

One of the challenges raised by the participants was a lack of belief in their abilities for preventive measures and preparation. According to Bandura, self-efficacy is the most important predictor of behavior change. If people believe they cannot perform a behavior, they are not motivated to act or resist challenges and obstacles (17). Studies have shown that the higher a person's self-efficacy is, the more intention there is for preventive measures and preparedness against disasters. In a review conducted by Ranjbar et al., Iranians who had more self-efficacy reported more earthquake preparedness behaviors (23). In Ning et al.'s study in China (2021), people with higher self-efficacy had more emergency preparedness behavior (8). In a study by Greer et al. in the United States (2020), it has been shown that the higher the self-efficacy of individuals, the higher their intention to prepare (30). People are likely to engage in preventive and disaster preparedness behaviors if they are confident in their ability to perform actions. As a result, attempting to improve the skills of households in various fields may lead to a sense of self-efficacy and increased efforts for preventive measures and preparation.

Some of the participants in this study stated that sometimes taking preparedness measures at home may negatively affect their family members, especially vulnerable groups. Therefore, they prefer not to prepare their family members for an earthquake to avoid physical and mental damage. According to the social-cognitive theory, if people believe that their actions to promote health will have more negative consequences than positive ones, they will stop that behavior (17). In Najafi et al.'s study, some of the interviewees stated that the main disadvantage of preparing for an earthquake is creating anxiety in family members (18). In studies conducted by Kelly and Ronan in Australia and New Zealand (31), Azim and Islam in Saudi Arabia (29), and McIvor et al. in New Zealand (32), negative outcome expectations were a negative predictor of disaster preparedness. Therefore, interventions focusing on informing people about the importance of preparedness and its benefits for vulnerable groups and their families should be prioritized.

Challenges related to behavioral factors

In this research, the participants believed that the lack of necessary skills makes households unable to take the necessary and appropriate measures to save their lives or others in the event of an earthquake. In the study of Ning et al. in China, people who had the skill to do drills and did them regularly were more prepared (8). One important stage of preparation is acquiring the necessary skills, such as first aid, search, rescue, firefighting, drills, etc. Therefore, to improve households' preparedness level, it is necessary to focus on increasing their skills. And in every household, at least one person should learn the mentioned skills.

The interviewees believed that the behavior of most people before, during, and after the earthquake was inappropriate. They were concerned that their emotional behavior during an earthquake would cause more harm to themselves and others. And they stressed that people's behavior should be corrected with proper training before the earthquake.

The participants stated that one of the people's behaviors during an earthquake is to go to the earthquake-affected areas, which can cause many problems, including more damage to the injured, disruption of aid delivery, etc. According to the participants, the presence of volunteers that do not have the necessary skills is one of the most critical challenges during an earthquake. In the Sharifi et al. study, many volunteers entered the area spontaneously after the Kermanshah earthquake. Some volunteers had not even received specialized training in rescuing and transporting the injured, which increases the possibility of injuries in the rescue process (20). Volunteers can be an excellent opportunity to overcome problems in many situations, but volunteers can also create challenges and problems if they are not properly managed and organized.

Challenges related to physical environment

One of the crucial challenges raised by most of the participants was the building of unsafe and non-resistant buildings. One of the most important basic measures to reduce the vulnerability and preparedness of households against earthquakes, especially in areas with high seismic risk, is the construction of standard and resistant houses. The results of various studies show that residential buildings in Iranian cities are dilapidated. For example, the results of Rezaei and Nouri's study (2017) showed that households in Kerman city are vulnerable to earthquakes in terms of building strength (33). In the study by Armas et al. in Romania (2018), 82% of residents believed that an earthquake was likely; however, only

3% believed their building would not suffer significant damage following a major earthquake (28).

Based on the interviews, some participants believed that other preparation measures are useless when the building is not resistant. In the study of Tekeli-Yeşil et al. in Turkey, households that were sure of the resistance of their building were more prepared, and their information was more about earthquake preparedness measures (19).

Considering that the most essential measure to reduce the vulnerability of households, especially in areas with high seismic risk, is the construction of standard and resistant houses, special attention should be paid to this issue (34). For example, construction should be monitored, and non-standard and illegal houses should be prevented from being built in the suburbs. Also, households with dilapidated houses should be encouraged and supported for renovation or reconstruction.

One of the barriers mentioned by the households was non-structural factors. Although building features are the most critical factor in earthquake mortality, even in the safest structures, if the furniture, equipment, and appliances inside the building are not safe, death and injury can occur. Some participants stated they faced barriers, including living in rental housing, to non-structural vulnerability reduction measures. Other studies showed that homeowners were more prepared for disasters (9, 16, 35). This is probably because homeowners have greater freedom of action to reduce structural and non-structural vulnerability or enjoy a higher socio-economic level. Since most non-structural vulnerability reduction measures, such as securing, immobilizing, moving, proper arrangement of furniture, etc. can be improved with minimal cost and facilities, this challenge can be overcome by designing educational programs for households.

The lack of manual and basic debris removal equipment was a significant problem raised by the Bam and Zarand earthquake survivors. Most participants thought that emergency equipment only included the first aid box. Only those who had previously experienced a devastating earthquake considered manuals and tools necessary for removing debris, in addition to other equipment. Therefore, drawing on the experiences of those who experienced destructive earthquakes can be very helpful.

Some of the participants believed that the narrowness of the roads in the city center, where most of the buildings are not resistant to earthquakes, is one of the critical challenges that must be solved before an earthquake occurs. In areas where the houses are dilapidated and the roads are narrow, in the event of an earthquake, rescue vehicles can't travel, and rescue forces can only provide services with a delay, which will increase casualties and serious complications among the injured. Studies have shown that cities in most regions of Iran are highly vulnerable to earthquakes. For example, in Mesri Alamdari et al.'s (36) study, a significant percentage of Varzeqan city was vulnerable to earthquakes. High residential and population density, low-quality buildings, and a lack of urban open spaces have caused this region to have a severe vulnerability to earthquakes (36). In the study of Salehipour Milani et al. (37), most Razan neighborhoods were close to 55% in the high and very high-risk range. The weak structure of the buildings, the age of the buildings, the narrowness of the roads, and especially the population density, were important factors affecting the city's vulnerability (37). Knowing weak and sensitive areas to earthquakes is the first step in reducing vulnerability to earthquakes and optimizing urban spaces. Therefore, it is necessary to identify vulnerable areas in every city and take urgent action to remove obstacles and problems.

Challenges related to the social environment

The participants believed that one of the most critical issues during an earthquake is providing security by the police and security forces. They believe that if people do not feel secure, they will not evacuate their homes during an earthquake warning. The evacuation order may cause chaos in the city, and there is a possibility of robbery if the house is evacuated. Also, vulnerable groups, including women and young girls, do not have the possibility of staying outside the house due to the possibility of causing harassment. In a study by Newnham et al. in Hong Kong, many participants mentioned fear of home burglary and lack of a suitable place to stay as factors preventing evacuation during a warning (10). Therefore, people's security should be ensured in all areas so that they can collaborate in evacuating their homes after the warning.

One of the challenges expressed by the interviewees about the preparation of households before the earthquake was insufficient interactions between family members, relatives, and community members. They believe that communication between people has decreased compared to the past for various reasons. They believed that the more people communicated with one another, the better they could support one another in various fields and help one another overcome obstacles. According to the study by Kim and Zakur, people who had higher levels of social support and more connections with society and organizations were more prepared for emergency situations related to disasters (38). A study conducted by Yong and Lemyre on Canadian households showed that receiving social support plays a role in disaster preparedness behavior (39). According to Kanakis and McShane's study conducted in a rural community in Australia that was prone to floods and storms, the higher the perceived social connections, the higher the disaster preparedness behavior of households (40). Social connections can contribute to knowledge sharing, financial support, emotional support, etc. When people are in contact with each other and support each other, they give a faster and more appropriate response to an emergency and recover and rehabilitate faster after disasters.

The non-participation of residents in preventive measures and preparations against earthquakes in the neighborhood was one of the other challenges. In the study of Hadafi et al., in Iran (2021), the participation rate of citizens was at a relatively favorable level, and most of the citizens had a lot of participation in voluntary activities to prepare against the risks related to the neighborhood (41). In the study by Becker et al. based on the interviews conducted with households living in New Zealand, the more the households participated in social groups, the more preventive measures and earthquake preparedness they took (42). People who participated in social activities had more intentions to prepare for earthquakes, according to Zaremohzzaieh et al. in Malaysia (2021) (43) and Adhikari et al. in Nepal (2018) (44). According to Kelly and Ronan's study in Australia and New Zealand (2018), people who participated in discussions about current events and participated in social events were more prepared for earthquakes (31). Social connections can contribute to knowledge sharing, financial support, emotional support, etc. When people are in contact with each other and support each other, they give faster and more appropriate responses to emergencies and recover and rehabilitate faster after disasters.

Challenges related to financial factors

Almost all participants mentioned financial issues as an essential barrier to preparing households against earthquakes. Buying land in safe areas and building a durable and standard house requires a lot of financial resources that most people may not be able to provide. Some of the participants stated that they could not renovate their homes or buy emergency equipment and supplies due to insufficient income and the increase in other living expenses. They preferred to spend their meager income on daily necessities.

Studies have shown that people with high income levels are more prepared for disasters (10, 31). In the study of Rezaei and Nouri, households with a higher socio-economic level had more knowledge, attitudes, and preparedness against earthquakes (33). In Newnham's study in Hong Kong, in people with higher monthly income, self-efficacy was higher and evacuation barriers were lower when hazards occurred (10). Therefore, the authorities' efforts to reduce society's financial vulnerability need to increase their preparedness against disasters.

Limitations

The interviews were conducted during the COVID-19 pandemic. Some households did not want to participate in the interviews due to the possibility of disease transmission. Some women and most men were working, so the interviews were conducted in the afternoons or on holidays when they were at home.

Conclusion

Participants in this study expressed several cognitive, behavioral, social, physical, and financial challenges. Many barriers and challenges can be solved by developing and implementing educational programs. Many of these challenges, however, cannot be overcome by households without the assistance of the government and officials. By removing the challenges and barriers, adopting preventive measures, and improving the level of preparedness, it is possible to decrease the casualties after earthquakes.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The Ethics Committee of Kerman University of Medical Sciences approved this study. A Qualitative design was employed in 2021. The code of Pajouhan is 400000068 and the ethic approval code is IR.KMU.REC.1400.719. All methods were performed in accordance with the relevant guidelines and regulations; this article does not contain any studies with animals performed by any of the authors. Informed consent was obtained from all individual participants included in the study written informed consent was obtained from individual participants. Confidentiality and anonymity of the participants were ensured by coding of the questioners. Study participants were informed clearly about their freedom to opt out of the study at any point of time without justifying for doing so.

Author contributions

The study's concept and design were created by ER. The survey was performed by NK. Data analysis and manuscript writing were handled by HF and MN-M. NK oversaw the research and provided critical feedback on the manuscript. The final manuscript was read and reviewed by all authors.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Water supply emergency preparedness and response in health care facilities: A systematic review on international evidence

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Introduction: Enabling health care facilities to deal with impairments or outages of water supply and sewage systems is essential and particularly important in the face of growing risk levels due to climate change and natural hazards. Yet, comprehensive assessments of the existing preparedness and response measures, both in theory and practice, are lacking. The objective of this review is to assess water supply and wastewater management in health care facilities in emergency settings and low-resource contexts. It thereby is a first step toward knowledge transfer across different world regions and/or contexts.

Method: A systematic review was performed to identify published articles on the subject using online MEDLINE and Web of Science. The initial searches yielded a total of 1,845 records. Two independent reviewers screened identified records using selection criteria. A total of 39 relevant studies were identified. Descriptive analyses were used to summarize evidence of included studies.

Results: Overall, water supply was far more discussed than wastewater management. Studies on emergency preparedness identified back-up water storage tank, additional pipelines, and underground wells as key sources to supply health care facilities with water during an emergency. In emergency response, bottled of water, followed by *in-situ* back-up water storage tanks previously installed as part of disaster preparedness measures, and tanker trucks to complete were most used. Questions on how to improve existing technologies, their uptake, but also the supplementation by alternative measures remain unanswered. Only few guidelines and tools on emergency preparedness were identified, while multiple studies formulated theoretical recommendations to guide preparedness. Recovery planning was rarely discussed, despite many studies mentioning the importance of the reconstruction and restoration phases. Literature focus on recovery is mostly on technical aspects, while organizational ones are largely absent. Despite their key role for preparedness and response, citizens and patients' perspectives are hugely underrepresented. This fits into the bigger picture as communication, awareness raising and actor cooperation in general is addressed comparatively little.

Discussion: Combining organizational and technical aspects, and intersecting theory and practice will be necessary to address existing gaps. Improving both, preparedness and response, is key to maintaining public health and providing primary care.

KEYWORDS

water supply and wastewater management, health care facilities, emergency preparedness, disaster response, risk assessment, low-resource contexts

Introduction

The provision of basic water, sanitation and hygiene (WASH) services in health care facilities (HCF) is essential for maintaining public health and providing primary care, i.e., safe and accessible water supply, on-site sanitation, hygiene facilities and waste management. Despite making WASH a core priority under Sustainable Development Goal No. 6 and significant progress in the last decades, in 2021, more than one out of five health care facilities worldwide had no basic water services (1). With significant impacts on infrastructure and provision of services, lack of access to WASH can contribute to the spread of diseases and increase health care-associated infection within HCF and surroundings (2). This is especially true for the most vulnerable populations and environments, e.g., marginalized and economically disadvantaged groups, humanitarian emergencies and crisis settings, post-disaster shelter, refugee camps, which are disproportionally affected by lack of basic services (3).

In a context of rising climate uncertainties and emerging threats, WASH and health infrastructure are subject to ever-increasing fragilities (4). Human and environmental hazards, e.g., climate or extreme weather events, armed conflict and terrorist attacks, and water supply failures or disruptions (e.g., due to power outages, dam failure, chemical spill), increase risk and may compromise the reliability of basic services. The COVID-19 pandemic is a stark reminder of ongoing global challenges and adverse effects on critical health infrastructure, e.g., deficiencies of health care facilities due to lack of preparedness (5).

Effective water management and disposal strategies, in normal times and crisis events, are essential to enable health infrastructures to deliver health services (6, 7). Level of supply reliability and standards can significantly affect needs in case of service disruption. Low-awareness and high dependency to continued services are considered determinant factors of fragility (8). For example, in settings with a continuous water supply, higher quantities of water will be expected to reach limited level of service and cope with intermittency.

To minimize the impact and avoid cascading failures of other critical systems, water supply utilities and health care facilities must withstand by themselves and ensure that basic services are provided and can recover in the case of emergency events and disasters (9). Substantial efforts and investments toward basic needs assessment, emergency preparedness and response are required worldwide, and this is necessary to bridge existing gaps between emergency and development (10). Although crisis events generally capture more attention, improving strategic planning at all stages from prevention and mitigation to long-term recovery is primordial. Despite learning from devastating impacts, inadequate application and implementation of emergency preparedness and capacity response assessment persist (11). The challenges that relate to emergency water supply and treatment in health care facilities are frequently overlooked and under-documented.

This systematic review focuses on the provision of water and sanitation services and health care facilities in emergency settings and low-resource contexts. While emergency settings can be defined as an unexpected, especially dangerous situation which threatens human, material, economic or environmental assets, we focus in particular on emergency settings which threaten the water supply or waste water management of health care facilities. One example is last year's flood in the states of Rhineland-Palatinate and North Rhine-Westphalia, which particularly affected the water supply of flood-affected health care facilities. Similarly, as low-resource contexts is an umbrella term that indicates a deficiency in a variety of areas, we specifically looked at settings where the water supply was unreliable. An example might be the northern remote communities in Canada where water is supplied with truck-to-cistern. Both of these contexts can occur in high-income countries as well as in middle- and low-income countries.

The objective of this systematic review is to provide an overview of the existing preparedness and response measures and strategies that have been theorized and/or implemented to enable health care facilities to access water supply and wastewater management to maintain their operations in the event of a disruption or impairment. The specific objectives are twofold: (1) to examine existing international standards and guidelines for emergency water supply preparedness in health care facilities, and (2) to identify preparedness and response strategies, technical and organizational interventions and recovery plans for the provision of water supply and waste water management. By reviewing international evidence and providing an overview on the range of approaches to deal with past emergencies but also low-resource contexts this review closes a research gaps and is a first step toward knowledge transfer across different world regions and/or contexts. The review aims to answer the following question: What emergency preparedness and response measures and guidelines for water supply and wastewater management for health care facilities can be found through a systematic review of the scientific literature?

Methods

This systematic review was conducted following the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) (12).

Eligibility criteria

Studies that focus on water supply in health care facilities in emergency settings and low resource contexts were sought for inclusion in this study. The systematic review was conducted using only peer-reviewed literature searches. English was consistently used to yield searches. No restriction related to the publication language or date of coverage were, however, applied for the initial search.

Information sources

A comprehensive literature search of peer-review publications was done through MEDLINE and Web of Science.

Search strategy

The search strategy includes general sets of criteria related to water supply and health care facilities in low resource contexts including vulnerable and economically disadvantaged groups (e.g., low-and middle-income settings, Indigenous populations, refugee camps) as well as humanitarian emergencies and crisis settings. The peer-review literature was identified through databases tailored search using a combination of basic terms and subject terms that relates to the sets of criteria (i.e., context, water supply and waste water management, health care facilities, disaster planning and response) as well as controlled vocabulary search terms, including index or MeSh terms (e.g., Disaster, Water supply, Health facilities). The overall search strategy, including definitions of sets of criteria, is available as Supplementary material.

Selection process

The selection process followed the PRISMA chart flow and guideline (13). The literature search was performed by one author, and records were retrieved in April 2022. The identified records were extracted using EndNote X9. Records published before 2000 and duplicates were removed before initial screening. The title and abstract of identified records were screened for eligibility by two independent reviewers (Heijden S. and Cassivi A.), and in case of any disagreement a third reviewer (Sandholz S.) was consulted for consensus. Full text of eligible studies, including peer-review articles, conference proceedings and reports, was assessed for eligibility using inclusion and exclusion criteria (Table 1). Records including reports and studies using empirical evidence that relates to water supply for health care facilities in low-resource contexts and/or emergency settings were sought for inclusion.

Data extraction and synthesis

Data from included studies was extracted and compiled using a structured form (available on request). Extracted data included general descriptive and contextual information on water supply and health care facilities, actors and coordination efforts, as well as specific information on emergency preparedness, response and recovery. Studies were finally classified in general categories and analyzed using descriptive analysis and qualitative evidence synthesis. Due to the observed heterogeneity of selected evidence, no pre-defined tool for the assessment of quality of evidence was used. Synthesis from overall study assessment was included and quality assessment was reported independently when relevant.

Results

Selection of sources of evidence

The initial search yielded 1,845 records. A total of 310 records were published before 2000 and 343 duplicates were initially excluded. Of the records eligible, 1,101 records were screened for title and abstract eligibility. Overall, 84 records were assessed for full text eligibility, of which 39 records were selected for inclusion in the systematic review. The search strategy and study selection are presented in the flow chart diagram (Figure 1).

Summary of study characteristics

A prospective approach, through emergency preparedness and response capacity assessment, was used in forty percent

TABLE 1 Inclusion and exclusion criteria for selection of records (SPIDER).

	Inclusion	Exclusion
Sample	Settings/population: - Health care facilities, e.g., hospitals, clinics. - Low resource context, e.g., LMIC - Emergency, humanitarian settings	Settings/population: - Households or domestic settings - School or educational facilities - Veterinary or animal clinics
Phenomenon of interest	Research area: - Preparedness for water supply emergency and wastewater management - Provision of drinking water and other purposes. - Critical water uses in HCF - Evaluation of water supply - Response/Interventions/Mitigation measures/Solutions for water supply and wastewater management - Lessons learned from emergency water supply.	Research area: - Status of WASH coverage, conditions and compliance - Engineering technology and applied sciences - Epidemiological studies/ Public Health threats/ Health-associated infections - Hygiene practices/Environmental conditions - Water quality monitoring and environmental surveillance, e.g., Legionella contamination. - Pollution, e.g., pharmaceutiques components - Quality of health care service and satisfaction - Human resources and health care workers - Medical or medicine supply. - Financing mechanisms/Cost analysis - Models or simulations - Antibiotics resistance/residuals
Design	Any design	
Evaluation	Subjective or empirical evidence	
Research type	Qualitative, quantitative or mixed	

of the studies while the remaining used a retrospective case report approach (Table 2). Overall, all (13 studies) but one study focusing on emergency preparedness were conducted in normal times, prior to an event of water supply and/or power supply emergency. Remaining studies, among which most are case disaster reports, were conducted in the event of a natural hazard-induced disaster (e.g., earthquake, flood, hurricane, COVID-19 pandemic). Case studies (23 studies) were conducted in a large range of different types of health care facilities, including hospitals (23 studies), disaster-based hospitals (4 studies), primary health care centers, and medical centers (13 studies), with a number of beds ranging from 18 to 1,000. Studies generally covered water supply and provision within health care facilities, and very few studies also discussed wastewater (5 studies) management. Finally, most studies included were conducted in high-income countries (25 studies), and the United States and Japan accounted for nearly half of the studies. Low- and middle-income countries (14 studies) were represented with individual studies from Cameroon, China, Haiti, Indonesia, Iran, Malaysia, Nepal, South Africa, Sri Lanka and Zambia. Two additional studies were, respectively, conducted worldwide and used a fictional country as a case study (Table 3).

Results of syntheses

Preparedness measures implemented in the event of water supply outages or impairments, existing guidelines and tools to prepare for this scenario, and written recommendations for improving preparedness (17 studies) were discussed in the literature. Many studies also address measures, tools and plans implemented as a response in the event of water supply outages or impairment (22 studies); and only a few look at the issue of recovery planning (5 studies).

Emergency preparedness

In most cases (17 studies from the 39 included), published literature on emergency water supply relates to risk assessment and emergency preparedness measures (Table 4). While some studies offered a general overview of preparedness measures, most studies performed an in-depth analysis of preparedness measures to prepare for a water impairment or outage. Examples of preparedness measures included implementation of emergency alternative water supply (e.g., emergency water tank) as well as emergency preparedness tools and plans for health care facilities (e.g., the hospital safety index). Among all studies, 11 studies that relate to emergency preparedness discussed the role

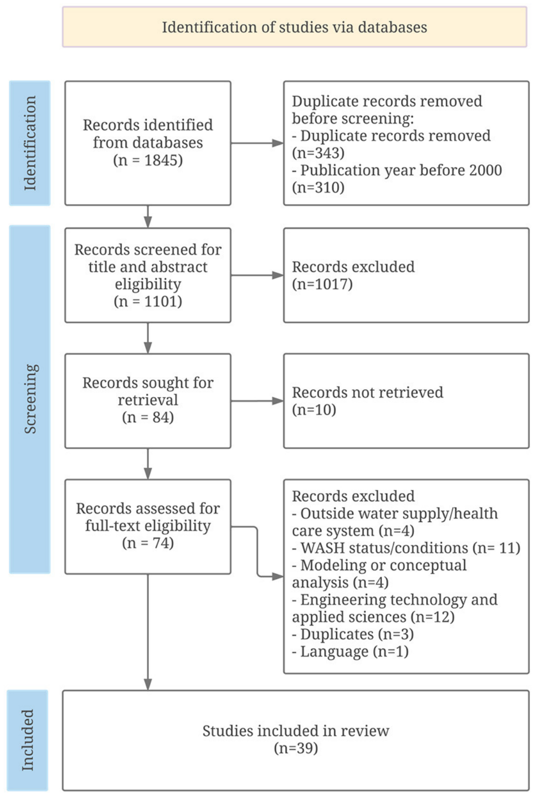

FIGURE 1
PRISMA Flow chart for study selection.

TABLE 2 Classification of the selected studies ($N = 39$).

Classification	Studies
Disaster case report	59%
Risk assessment and preparedness	41%
High income countries	64%
Middle and low income countries	36%
Studies with implemented preparedness measures	26%
Studies with implemented response measures	46%

of various stakeholders in facilitating networking and planning in the context of an emergency.

Emergency alternative water supply

In the event of water impairment or outage, the provision of water supply is a priority to minimize the risk of service disruption. Overall, 10 studies discussed the implementation of emergency water supply preparedness measures in health care facilities (Table 4). Common measures included back-up water storage tanks, additional pipelines, and underground wells.

The installment of on-site water storage tanks as a preparedness measure was described in six studies, among which more than half were conducted in Japan in the aftermath of the 2011 Great East Japan Earthquake disaster (29, 34, 39, 47). Results from one study conducted in 134 disaster-based hospitals in the capital area of Japan show an average water tank capacity of 8.32 l/m2, providing hospitals with water for approximately one day, if planned accordingly, in case of an emergency (29). In a study conducted in Miyagi Prefecture, the majority of the 14 disaster-based hospitals had water storage capacity of less than a day, highlighting the need for a clear water allocation plan (34). In large Japanese university facilities (650–800 beds), a large water tank of 700 m3 and dual water tanks of 160 m3 each, respectively, would allow to supply for approximately one day based on an approximate daily consumption of 500–600 m3 on peak weekdays (39, 47). Results from a survey conducted in 54 major health care facilities (i.e., hospitals, health centers and health posts) in the Greek Islands show that more than two third (70%) of facilities had a backup water tank available, among which half of the hospitals reported having reserve of water for three or more days (15). In the United States, as part of a hurricane-protection master plan, a children's hospital in New Orleans has installed 4 water tanks of 15 m3 each to provide water in the event of an emergency (40).

The implementation of external hook-ups for permanent water hoses and/or piping in disaster-based hospitals and academic medical centers was described in four studies as a measure to prepare for water outages or impairments (21, 27–30). After Hurricane Katrina, a large medical center (700 beds) in the United States installed external hook-up for emergency water supply in its new buildings as well as a back-up groundwater well to supply air conditioning chillers (HVAC) (21). Similarly, in the aftermath of a chemical spill in West Virginia, two hospitals in the United States proceeded to the installation of water-intake site where tanker trucks would be able to deliver water in case of emergency (27). To prepare for earthquakes, one disaster-based hospital in Japan designed internal mixed water systems with double water pipelines for the hemodialysis center: one main line supplied with tap water and well water and one back-up pipeline connecting the well to the hemodialysis center (28). Similar dual systems exist elsewhere, for example, in Malaysia internal water supply systems in hospitals were generally divided into two sub-systems for facility usage (e.g., chillers and air-conditioning systems, medical equipment) and staff or patient usage (e.g., dialysis services, laboratories, surgery wards and sanitation facilities) (30). Results from a survey conducted in 134 disaster base hospitals in Japan show that the number of hospitals that use well water, rainwater, and reclaimed water systems have increased recently, with a respective adoption rate of 30, 17, and 30% (29).

Emergency water supply plans and tools

Guidelines and tools to assess and improve the state of emergency preparedness for water supply outages or

TABLE 3 General characteristics of included studies ($N = 39$).

References	Type	Countries	Sample (Number HCF[a], type[b], number of beds[c])	Emergency situation	Event
Adhikari et al. (14)	Disaster case report	Nepal	NS, health facilities, NS	Natural hazard-induced disaster	Occurred
Alexakis et al. (15)	Risk assessment and preparedness	Greece	54 health facilities, 18 to 500 beds	Water and/or power supply emergency	Hypothetical
Ateudjieu et al. (16)	Risk assessment and preparedness	Cameroon	134 health facilities, NS	Health emergency (outbreak)	On going
Ballantyne (17)	Disaster case report	Sri Lanka	NS	Natural hazard-induced disaster	Occurred
Dippenaar (18)	Risk assessment and preparedness	South Africa	1 hospital, 334 beds	Water and/or power supply emergency	Hypothetical
Bichai et al. (19)	Risk assessment and preparedness	Worldwide	NA	Health emergency (outbreak)	Occurred
Bross et al. (7)	Risk assessment and preparedness	Germany and Austria	NS, health facilities in Germany (256 beds average) and Austria (239 beds average)	Water and/or power supply emergency	Hypothetical
Bross and Krause (20)	Risk assessment and preparedness	Germany	NS. hospitals, NS	Water and/or power supply emergency	Hypothetical
Cdc Environmental Health Services Branch (21)	Risk assessment and preparedness	USA	Case Study No. 1: 1 academic medical center, 700 beds Case Study No. 2: 1 Nursing home, 165 beds	Water and/or power supply emergency	Hypothetical
deBoisblanc (22)	Disaster case report	USA	1 hospital, 500 beds	Natural hazard-induced disaster	Occurred
Gray and Hebert (23)	Disaster case report	USA	dozen hospitals, NS	Natural hazard-induced disaster	Occurred
Haar et al. (24)	Disaster case report	Haiti	59 health care providers, NS	Natural hazard-induced disaster	Occurred
He et al. (25)	Disaster case report	China	1 temporary hospital, 1,000 beds case study	Health emergency (outbreak)	Occurred
Heidaranlu et al. (26)	Disaster case report	Iran	8 hospitals, 60 to 980 beds	Natural hazard-induced disaster	Occurred
Hsu et al. (27)	Disaster case report	USA	10 health facilities, 25 beds and more HCFs	Chemical emergency	Occurred
Ikegaya et al. (28)	Disaster case report	Japan	1 disaster base hospital, 712 beds	Natural hazard-induced disaster	Occurred
Inagaki and Sadohara (29)	Risk assessment and preparedness	Japan	134 disaster base hospitals, NS	Natural hazard-induced disaster	Hypothetical
Janius et al. (30)	Risk assessment and preparedness	Malaysia	5 government hospitals, NS	Water and/or power supply emergency	Hypothetical
Klein et al. (31)	Disaster case report	USA	4 hospitals (3 trauma centers and 1 children's hospital)	Power and water emergency	Occurred
Lapcevic et al. (32)	Risk assessment and preparedness	Serbia	1 hospital, 336 health care workers	Natural hazard-induced disaster	Occurred
Lestari et al. (33)	Risk assessment and preparedness	Indonesia	11 hospitals, NS	Water and/or power supply emergency	Hypothetical

(Continued)

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TABLE 3 (Continued)

References	Type	Countries	Sample (Number HCF[a], type[b], number of beds[c])	Emergency situation	Event
Matsumura et al. (34)	Disaster case report	Japan	14 disaster base hospital, NS	Natural hazard-induced disaster	Occurred
Mitchell et al. (35)	Disaster case report	USA	1 hospital, NS	Natural hazard-induced disaster	Occurred
Nates (36)	Disaster case report	USA	1 medical center, 28 beds intensive care unit	Natural hazard-induced disaster	Occurred
Ochi et al. (37)	Disaster case report	Japan	147 hospitals, NS	Natural hazard-induced disaster	Occurred
Paez et al. (38)	Risk assessment and preparedness		NA	Water and/or power supply emergency	Hypothetical
Parmar et al. (39)	Disaster case report	Japan and USA	1 hospital, 778 beds	Natural hazard-induced disaster	Occurred
Perrin (40)	Disaster case report	USA	1 tertiary hospital, 54 beds	Natural hazard-induced disaster	Occurred
Redfern et al. (41)	Disaster case report	USA	1 tertiary hospital, 794 beds	Water and/or power supply emergency	Occurred
Roberson and Hiltebrand (42)	Risk assessment and preparedness	USA	NS, health facilities, NS	Water and/or power supply emergency	Hypothetical
Ryan et al. (43)	Disaster case report	Australia	No sample, public health infrastructure, NS	Natural hazard-induced disaster	Occurred
Salfarlie (44)	Risk assessment and preparedness	USA	1 hospital, NS	Water and/or power supply emergency	Occurred
Shimoto et al. (45)	Disaster case report	Japan	9 hospitals, NS	Natural hazard-induced disaster	Occurred
Sinyange et al. (46)	Disaster case report	Zambia	267 household	Health emergency (outbreak)	Occurred
Suginaka et al. (47)	Risk assessment and preparedness	Japan	1 university affiliate hospital, 653 beds	Natural hazard-induced disaster	Occurred
Wahren et al. (48)	Disaster case report	Poland and Sweden	NA (health care system)	Natural hazard-induced disaster	Occurred
Welter et al. (49)	Risk assessment and preparedness	USA	1 regional health center	Natural hazard-induced disaster	Occurred
WHO (50)	Disaster case report	Haiti	NS, health facilities, NS	Natural hazard-induced disaster	Occurred
Yusoff et al. (51)	Disaster case report	Malaysia and overseas	NS, hospitals, NS	Natural hazard-induced disaster	Occurred

[a]health care facilities; [b]used term to describe the facility in which primary health care is provided (e.g., hospital, health center, clinic, dispensary etc.); [c]not specified.

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TABLE 4 Implemented preparedness measures for emergency water supply in health care facilities in the literature (*N* = 10/39).

Implemented measures	Number of studies	References
Water tanks	6	(15, 29, 34, 39, 40, 47)
Additional pipes	4	(21, 27, 28, 30)
Wells	3	(21, 28, 29)
No reference to implemented preparedness measures	29	All other papers from the literature review

TABLE 5 Preparedness tools for emergency water supply in health care facilities in the literature (*N* = 10/39).

Tools	Use	Number of studies	References
American EWSP	Presentation, reference and critics	5	(18, 21, 42, 44, 47)
HSI	Assessment, recommendations and critics	4	(15, 26, 32, 33)
South African water supply risk management and response plan	Assessment and recommendations	1	(18)
Disaster action plan for critical engineering	Assessment	1	(30)
BIA	Assessment	1	(47)
No tool mentioned and used	NA[a]	29	All other papers from the literature review

[a]NA, non-applicable.

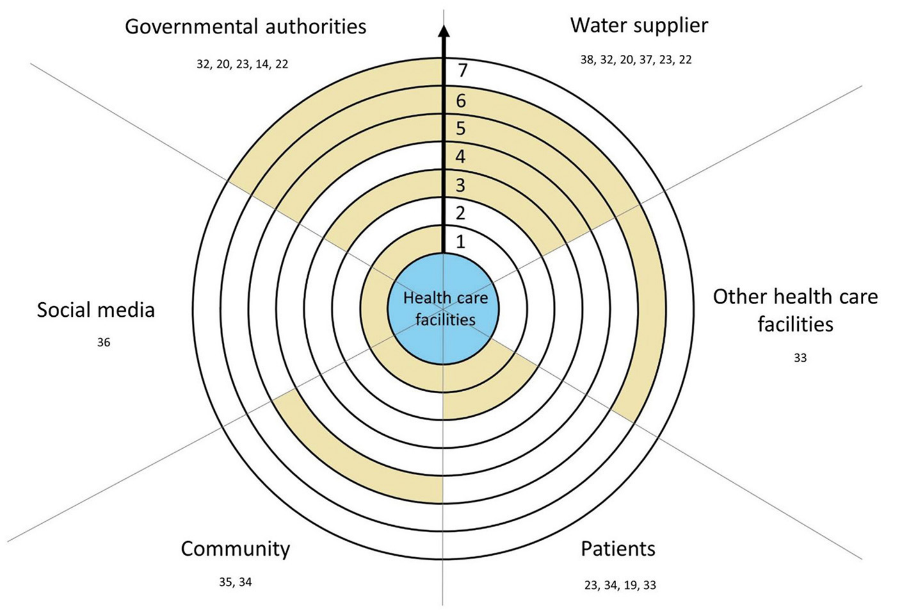

FIGURE 2
Recommended involvement of stakeholders in health care facilities preparedness. Scale: (1) Consideration, (2) Raising awareness, (3) Dialog, (4) Regular meetings, (5) Plan, (6) Agreements, (7) Legislation. Color: Yellow, Recommended level of involvement in the preparedness; White, Nothing recommended; Blue, Health care facilities. →, Progression of the formalization of networking with health care facilities.

impairment were explicitly discussed in one quarter of the studies included in the literature review (Table 5). The Hospital Safety Index (HSI) and the American Emergency Water Supply Planning Guide for Hospitals and Healthcare Facilities (EWSP) were found to be the most used or referred guidelines for risk assessment and preparedness planning for water outages or impairments. Designed by the World Health Organization (WHO) and the Pan-American Health Organization (PAHO), the HSI has been used to assess hospital safety and subject of several studies worldwide (32). Without surprise, the HSI was identified as the most used tool to assess the state of health care facilities' preparedness in studies identified through this review. The application of the HSI varied according to the type of facility, e.g., hospitals, primary health care centers and health posts, hospital capacity i.e., ranging from 18 to 980 beds, in diverse locations e.g., Greece, Indonesia, Iran, Serbia. It was used to assess the health care facilities' non-structural safety, which included water supply systems, locations of water tanks, water quality control, sanitation systems, heating, ventilation, HVAC, and/or hot water systems. In Greece, Iran and Indonesia, the HSI was also used to formulate recommendations to improve water supply safety (15, 26, 33), whereas in Serbia the usefulness of the HSI for safety assessment of a primary health care center was further evaluated (32).

The EWSP is mainly presented as a reference tool for emergency preparedness. The EWSP was designed by the Centers for Disease Control and Prevention (CDC) and American Water Works Association (AWWA). Studies conducted in the United States highlighted the value of the EWSP standards to help health care facilities prepare, respond, and recover from a total or partial interruption of the facility's normal water supply (21, 42, 44). Studies from outside the United States, however, bring up a more skeptical perspective on the relevance of the EWSP (18, 47). For example, a study conducted in Japan broaches that the EWSP does not assign priority to operations or estimate daily water consumption in a fully operating hospital (47). In South Africa, the EWSP was further used together with the prevention, preparedness, response, and recovery model (PPRR) to develop a regional water supply risk management and response plan to reflect the institution's specific requirements (18).

A set of alternative assessment tools to prepare for emergency water supply in health care facilities were identified (18, 30, 47). One Japanese study used a business impact analysis (BIA) methodology applied to emergency water supply to analyze water use and prioritize water consumption in each department of a large hospital (653 beds) and the options for securing water in an emergency. The BIA aimed to optimize ways to use and conserve water and increases of hospital's abilities to manage disruption in the water supply (47). Similarly, a risk management plan for the continuous supply of water of hospitals was designed for hospitals in the Western Cape Province in South Africa (18). Reflecting institution's specific requirements, the risk management plan was adapted as general guidelines for the Western Cape Department of Health to assist in developing risk management and response plans for all its health care facilities. Lastly, a comprehensive hospital disaster action plan to face water and power supply was developed for five Malaysian hospitals using the Hazard Identification, Risk Assessment and Risk Control (HIRARC) guidelines for the risk analysis process as well as the UNISDR guidance note on Emergency and Disaster Preparedness for Health Facilities for the action plan (30).

Emergency preparedness and recommendations

Studies included in this literature review also provided recommendations on emergency water supply and waste water management (22 studies). They detailed different stages of preparedness and the responsiveness of actors and networks during a crisis.

Multiple studies have formulated recommendations on different stages to prepare health care facilities for a water outage or impairment (7, 21, 28, 34, 36, 47, 52). In addition to the general benefits of saving water, reducing water demand was identified as an important resource in case of emergency (18, 21). Health care facilities should enhance conservation practices and adopt technologies that are less water dependent in normal times. Integration of such principles will facilitate implementation of future contingent conservation protocols and further help to identify strategies to meet residual water requirements in case of emergency (52). Having a clear understanding of the priority of operations and of the initial water demand and minimum daily water requirements is a prerequisite before selecting feasible preparedness measures (18, 20, 28, 42, 47, 52). For example, this can include an evaluation and assessment of each unit or station water use as well as of hospital processes which could be maintained or replaced by waterless alternatives during emergency settings (8).

Health care facilities, particularly health care facilities whose support is expected in a disaster event, should have a clear understanding of the initial water demand and minimal daily requirements to meet specific facility needs. This is necessary to conceiving appropriate preparatory measures, including water allocation plans and water supply alternatives (20, 21, 28, 34). Attention was also driven on wastewater management and the need to consider systematic flushing plans in the preparedness, e.g., flushing toilets with non-potable water (20).

Provision of alternative water and wastewater services should be organized with all stakeholders to aim at rapid recovery and return to baseline function (36). Stakeholders mentioned in the reviewed papers as needing to be involved in the preparedness are governmental authorities, water suppliers, other health care facilities, patients, communities and social media (Figure 2). Papers mentioning these stakeholders also discuss the different ways in which health care facilities could engage with them, from informal to formal (consideration, raising awareness, dialog, regular meetings, plans, agreements, legislation). Overall, health care facilities, governmental authorities and water suppliers were identified as foremost stakeholders for water emergency preparedness and linked through trilateral or bilateral coordination efforts. Multiple

TABLE 6 Emergency response measures in the literature ($N = 18/39$).

Implemented emergency water supply	Number of studies	References
Bottled water	6	(17, 21, 22, 27, 31, 41)
Water tanks	6	(17, 34, 35, 39, 44, 47)
Water trucks	2	(7, 49)
Wells	5	(17, 21, 28, 34, 50)
Water supply treatment unit	1	(17)
Waste water treatment unit	1	(25)
Emergency plans		
Used for provisions of food, water, medications, security and physician	1	(23)
Used as a support to respond to the crisis	1	(40)
Used with modifications when necessary, including essential staffing, social media, water supplies, dialysis process, and communications	1	(41)
Actors involved in the implementation of emergency water supply		
Hospitals	6	(28, 31, 34, 35, 39, 47)
Private sector	6	(7, 17, 21, 35, 41, 50)
Rescue agencies (fire fighters, red cross etc.)	3	(17, 21, 44)
Governmental actors (regional/national authorities, army)	2	(49, 50)
Volunteers	1	(17)
International actors	1	(50)

studies also identified patients as important actors to involve in the emergency preparedness phase (28, 37, 40, 43). To a lesser extent, other health care facilities which are not affected by the outage or impairment, the community in which the hospital structure is located, and social networks are also mentioned as essential to enhance networking responsiveness and communication plans (23, 37, 41).

The formalization of the cooperation into plans and/or agreements is recommended to link governmental authorities, water suppliers, other health care facilities, communities and patients with health care facilities in the preparedness and response phase (19, 25, 28, 30, 43). Adopting sustained measures to ensure availability of emergency water supply can ease thought appropriate emergency and security legislation (28). Health care facilities need to be part of the emergency water supply plan of a municipality and considered when planning the distribution of water supply and should prepare according to the emergency water supply plan and capability of the local government (20, 29). Likewise, health care facilities and water suppliers should engage one another in their respective service areas to develop effective emergency operation plans for healthcare facilities, for example through regular disaster management meetings or memorandum (25, 28, 30). After the Great East Japan Earthquake, dialysis centers of the Fukushima Prefecture for example proposed a law to the local government to guarantee them priority over a certain amount of water in case of emergency.

Health care facilities play a central role in area-wide disaster and evacuation planning and emergency preparedness should be considered as a part of the reinforcement of community resilience (23, 37). Raising awareness about the importance of water in health care facilities is recommended with water suppliers and patients, for example using social media or fact sheets (41, 43). Multiple studies have further identified the patients as an important actor to involve in the emergency preparedness phase (28, 37, 40, 43). The broader community, including function of social media, was identified as essential to enhance networking responsiveness and communication plans (23, 37, 41).

Emergency response

A majority of the studies included in this review were disaster case reports retrospectively assessing emergency preparedness and response in health care facilities (23 studies). Emergency response following an occurrence of water supply outage or impairment was evaluated through various operations, including emergency water and sanitation services, emergency plans as well coordination and communication measures implemented.

Emergency water supply and sanitation services

Overall emergency water supply was generally provided through alternative sources coming either from inside or outside the health-care facility: bottled water, water tanks, water trucks, wells, water supply treatment unit, waste water treatment unit (16 studies) (Table 6). Efficiency of those measures and actors involved in the provision of water supply was discussed disparately in the literature.

Regardless of the type of emergency, e.g., earthquakes, or chemical spills, the most common and first hospital response was the provision of drinking water using bottled of water (17, 21, 22, 27, 31, 41). All studies, except one conducted in Sri Lanka, reported on disasters that happened in the United States. The provision of bottled water was eased in cases where hospitals had previously stored bottled of water on-or off sites (31, 41), otherwise they would rely on the local soft drink distributor. The use of couriers, for example to move the bottles through the hospital, was identified an important asset to facilitation emergency response. In Sri Lanka, in the first days after the 2004 Indian Ocean earthquake and tsunami, water was collected from bottling plants located in non-impacted areas and distributed in affected areas. Bottled of water was mainly used to provide drinking water to the patients, ensure basic hygiene practices (27, 31) and pursue some operations in the hospital e.g., limited food preparation (21), and irrigation of endotracheal tubes (22). After a water contamination in a municipal supply in the United States, the need for a memorandum of understanding with additional water suppliers for future emergency events was highlighted (41).

Case reports following natural hazard-induced disasters in Japan and Sri Lanka described the use of *in-situ* back-up water storage tanks previously installed as part of disaster preparedness measures in the affected health care facilities (17, 34, 35, 39, 47). Complementary or alternatively, tanker trucks were also reported as a common emergency external source to supply health care facilities (7, 34, 35, 39, 44). Water trucks can hook up directly to the hospital line, or in some cases to the back-up tank, or provide external supply. The availability of water trucks, quality of water as well as accessibility to health care facilities in affected areas were, however, identified as important challenges. For example, in Sri Lanka, first response was to deliver water from the truck in reused containers but this was later switched to bottled water because of water quality concerns (17). In the United States, in a case when no water was available from the municipal supply water trucks deliveries were arranged with a private construction company that had relationship with the hospital (35). In Japan, water trucks could supply the hospital with ∼100 tons of water daily, but this was not sufficient to continue hospital operations after a few days (39). Lessons from emergency case reports show the importance of having reliable access to external sources of supply, e.g., initiated with water trucks, but also highlight the need to provide alternate supply that is connected to the hospital line after a few hours or days (7, 35, 44). In an effort to restore services, water treatment plant units or reverse osmosis treatment systems were commonly deployed by the national guard in response to emergency events that lead to water disruptions (49).

Whereas, issues related to the water supply are often discussed in case reports, few studies mentioned alternative measures for the provision of sanitation services and/or wastewater management within the health care facilities during an emergency. After Hurricane Isabel in the United States, surveyed hospitals reported the cascading effect of the loss of water supply on sanitation facilities and hygiene (52). As an alternative, after Hurricane Ike, water from the hospital's physical therapy swimming pool was used to flush the toilets. In the construction of a hospital to face COVID-19 in China, wastewater treatment was prioritized, as a result a leakproof sealed collection system with high-density polyethylene anti-seepage was installed to ensure water quality standards in discharge water (25).

Similarly, some hospitals have installed underground wells to provide backup source of water in prevention and/or response to an emergency. In Japan, hospitals with connected wells were able to quickly obtain sustained volume of water and operate under basic conditions after the Great East Japan Earthquake (28, 34). In the United States, firefighters were also involved in the response by pumping well water into three 2 000-gallon dump pools and pumping the water into the hospital through its external hook-up (21). Findings from Sri Lanka and Haiti provide a different perspective as wells were originally used as a primary source of water. In Sri Lanka, wells were heavily damaged by the earthquake and tsunami, and could not be used as an alternative source until they were later restored by pumping out saltwater (17). In this case, international responders, e.g., Thai Red Cross, and Canadian Disaster Assistance Response Team, eased deployment of temporary water treatment units to support HCF during emergency responses, and later allowed to develop permanent water treatment facilities. In Haiti, the local authorities organized the collection and transportation of water from deep boreholes in the capital Port-au-Prince to priority facilities such as hospitals. The involvement of the WASH Cluster in Haiti allowed for water quality testing and chlorination to be performed before distribution to health care facilities (53).

Emergency plans and coordination

Appropriate response to emergency events highly depends on quickly implemented response measures, and this can be facilitated through existing emergency plans and coordination mechanisms (11 studies).

Nevertheless, the use of emergency plans was infrequently reported in case report studies. Overall, cases that reported the use of emergency plans referred to events that took place in the United States. For example, large hospitals in New Orleans developed extensive hurricane-protection master plans (23, 40). The state of preparedness as well as management of hospital operations allowed for quick implementation of the disaster plan days before and after Hurricane Katrina. Similarly, a large hospital system provided a quick response to a "do not drink, do not boil" advisory, using and adapting a designated emergency operations plan (41). The inability to communicate during the emergency was, however, cited as an important limitation to the implementation of emergency plans (23).

Considering that multiple stakeholders and actors are involved during a water emergency, integrating coordinating efforts and breakdown structures and roles is necessary. Emergency operation centers are of critical importance to coordinate operations and management of the infrastructure during and after a water crisis (31). In a Chinese COVID-19 temporary field hospital, an online communication platform, gathering different expert groups, was implemented to provide online technical guidance for the management of water and wastewater (25). Lack of coordination can have significant impact, particularly on the ability to respond quickly to an emergency. For example, during Hurricane Katrina, the last hospital to evacuate newborns was the one that couldn't rely on immediate assistance from contacts in other states or its parent organization (40). There is a need to integrate all stakeholders in emergency plans. In response to a cholera epidemic, the Ministry of Health in Zambia activated a national emergency operations center, using an incident management system to collaborate with other government ministries and partner organizations, e.g., CDC, Africa CDC, UNICEF, WHO, Zambia Red Cross, Médecins Sans Frontières, and others (46). Results from case studies conducted in Zambia, Haiti and Sri Lanka show that involvement of International Disaster Relief agencies can further facilitate the provision of services from a humanitarian to development perspective, e.g., temporary water treatment plants replace by permanent infrastructure.

When water is not readily available and/or emergency plans fail, countermeasures must be implemented by health care facilities. Damage to the water supply system will mainly influence the decision of health care facilities to relocate patients or evacuate as a response measure. The decision of a facility to evacuate will be based on its ability to ensure safety and meet the needs of the patients. Case studies conducted in the context of high impact natural hazard-induced disasters, e.g., hurricane, earthquake, and floods, shows that evacuation was necessary (22, 34, 36, 40, 45, 48). In some cases, total evacuation was completed in <36 h (22, 40). Various factors including viability of resources outside the hospital and damage to other critical infrastructure, e.g., exit routes, and transportation available, will influence response. A combination of internal and external coordination measures, including preparedness training, communications, evacuation of patients and involvement of volunteers, were identified as important factors to address emergency response (36). Various studies highlighted the importance of establishing an effective communication system. Use of informal channels such as social media can play an important role during a crisis, but, in some cases, fast media communication was also identified as a drawback (36), e.g., during a crisis in the United States, media information was shared more quickly than the updates from the hospital's emergency management team which caused confusion and interference with internal policies (41).

Recovery planning

Although it is important to look forward to the reconstruction phase and restoration of services (36) the preparation of recovery plans is rarely discussed in the literature. Five case reports from Japan and the United States, however, reconsidered emergency preparedness and self-sufficiency of health care facilities to rethink failure (21, 27, 31, 34, 41). Regardless of the type of emergency that was faced by health care facilities, i.e., chemical spill, interruption of service or massive damage to water supply, permanent measures were considered and/or implemented to reverse the impacts on services and prevent failures. Management group discussions and after-action review led, among other things, to changes in hospital policies and restructuration of infrastructure (31). Most health care facilities used engineering-based techniques to secure both existing and new infrastructure. For example, after a chemical spill in the United States, the affected hospital included a centralized water-shut-off mechanism and a water-intake site where tanker trucks could deliver water to existing renovation plans (27). Similarly, after Hurricane Floyd, a new non-permitted well with stand along water treatment plant as well as emergency water supply hooks up were installed in a large academic medical center in North Carolina, United States. Additionally, water-cooled systems of the same hospital complex were converted to air cooled to ensure essential functions (21). More extensively, the Ministry in Japan enhanced the earthquake resistance of disaster base hospitals, and as of 2012, 73% of disaster base hospitals and critical care centers were considered earthquake proof (34).

Discussion

This research aims at assessing existing preparedness and response structures and mechanisms to support water and sanitation services in health care facilities in the context of emergency settings and low-resource contexts. Studies were found in emergency settings, either in high-, middle- and low-income countries. The following section discuss the emergency preparedness and response measures, looking at if they were concretely implemented or part of recommendations, as well as where they were located. The lack of recovery measures and analysis of cascading impacts in the literature is also questioned. Gap in research on actor collaboration and cooperation is highlighted, particularly with regard to the role of citizens and patients.

Overall, the lack of available literature from low-resource contexts which are frequently dealing with impairments of water and sanitation services is concerning, as much can be learned from such contexts for emergencies in locations with less frequent disruptions. Only very few case studies were found in such contexts, while the majority of studies comes from the United States and Japan. Both countries are notably regularly affected by disaster events, mostly induced by natural-induced disasters and much can be learned from their mechanisms. Nevertheless, this poses a significant gap and leaves a somewhat one-sided picture.

Multiple sources of water can be used to supply health care facilities during an emergency. Given the urgency to act in case of water outages or impairments in health care facilities it is surprising that only 10 studies were found on emergency water supply preparedness measures. The key measures found, namely back-up water storage tanks, additional pipelines, and underground wells, however, seem universally applicable, and not limited to specific locations. Besides these sources few alternatives are mentioned, raising questions on how to improve existing technologies, and their uptake, but also the supplementation by other creative measures that are adapted to specific contexts, such as supply by water trucks (7, 34, 35, 39, 44). The availability of emergency *in-situ* water treatment is also important to provide safe water, but this was overlooked in most cases.

A potential reason for the lack of emergency supply measures–whether theoretically possible or already implemented–could be a related lack in water supply plans and tools. Comparably few health care facilities discussed in literature comprised of such plans, with the most frequently debated one being developed by international (e.g., WHO) or US American Organizations. Likewise, the case studies from the United States, that seem to have a well-referenced water supply plan, do not regularly mention its uptake. Few studies mentioned national tools from other countries, again Japan was one of the cases described (18, 47). This suggests, unsurprisingly, that concrete threats lead to more planning, such as the extreme earthquake risk in Japan (28, 29, 34, 39, 45, 47), hurricanes in the US (21–23, 35, 39, 41, 43, 52) or drought risk in South Africa (18) where the case studies with concrete policies and preparedness measures came from. Overall, the lack of plans mentioned in literature is concerning and has the potential to impede better preparedness. It remains to be analyzed whether this is because such plans are not considered worthy of research in the context of health care facilities. Even if they are described in detail in the gray literature, a gap remains.

The most significant and concrete on-site preparedness measures were found in Japan, where disaster preparedness has been a prioritized national agenda (54). This can be explained by the high risk of earthquakes and the associated preparation for such events, also in health care. All health care facilities analyzed in the review are comparably big and would be important supply points in case of a disaster. Japan also has a particular status for Disaster Base Hospitals (28), coming with legal obligations regarding water supply in times of emergency, namely tray water tanks of appropriate capacity and wells. Nothing comparable could be identified, although across papers a slight correlation between the facility size and overall preparedness could be found, in general small facilities tend to be less prepared than bigger ones. The reasons for this may be the lower availability of financial and technical resources, but also the lower staffing level, which usually does not provide for a specialized staff member for the topic. The absence of guiding documents and legal requirements may also play a major role for lack of preparedness, since especially for smaller facilities, own planning is probably not within the realm of possibility. However, it is precisely in these facilities that a large proportion of patients are cared for on a decentralized basis in case of a larger emergency.

Scientific literature that focus on recovery mostly discussed technical aspects, while organizational ones are largely absent. Whether this is due to the non-existence of such measures in reality or to a lack of research or a lack of adequate analytical tools to assess their efficacy remains unknown. However, it is reasonable to think that this is also due to a one-sided focus on the technical solvability of the water supply. The most commonly used response for provision of drinking water seems to be the use of bottled of water, raising the question of how long this might sustain functionality of the respective health-care facility that would usually have more critical functions needing water in larger amounts. Evidence from this review shows that, in most cases, evacuation was necessary when water couldn't be further provided (22, 34, 36, 40, 45, 48). The use of bottled of water is often necessary in the first hours after a disaster but should not be considered a viable option for long-term water supply, especially for other purposes than drinking. Wells seemed to be an interesting alternative to rapidly provide emergency water supply, particularly when connected directly to the main line through a back-up pipeline, again Japan is an example where comprehensive plans including the construction of wells to improve response (28, 29, 34). Water trucks were mentioned as an alternative supply source in different countries and contexts, however, papers usually fall short on assessing their viability in case of a larger crisis that might affect access to the respective facility, for instance if roads are blocked or flooded. Moreover, reliability of water trucks would also depend on existing infrastructure to distribute water following the disaster, e.g., external hook-up for emergency water supply and water tanks.

Overall, cascading impacts of any crisis on health care facilities were little discussed throughout preparedness, response and recovery. Sanitation during a crisis is looked at even less. This is concerning as for example a paper on US hospitals reported on hygiene problems due to lack of sanitation (22) which can easily disrupt functionality of health care facilities and delay the resumption of operation. Evidence from the field of WASH shows an international consensus on the impact of lack of access to water supply on the provision of sanitation and hygiene services, including in health care facilities (2, 55–57). Multiple papers from low-resource context, e.g., lower economies, that were initially retrieved from this systematic review were excluded as their main focus were overall WASH conditions and coverage of access. Given that WASH as overarching topic is very prominent the lack of research publications addressing it comprehensively for health care infrastructure is even more obvious. A potential reason is that WASH and basic service levels are usually associated with crisis or emergencies in low-resource contexts, where focus is often directed toward lacking services, and much less in countries or regions with high standards and security of supply (8). This is an opportunity missed to learn from low-resource contexts, overcoming challenges that relate to water supply, e.g., water intermittency in municipal water supply and wastewater management, which are well-known but rather scarce in research literature.

Another key finding of the analysis is the lack of recovery planning, which is mentioned in few publications only. However, it is exactly in this phase where learning from lack of preparedness or mistakes in recovery can be addressed and improved. Case studies found are from the United States (21, 27, 31) and Japan (34, 39) again, and link both, organizational and technical aspects. Concrete cases describe interventions to improve technical setups based on learning from failure. This remarkable step may also be the reason why so little is read about it-it requires a high degree of critical faculties and openness to make these mistakes in preparedness and recovery public. Likewise, there is a lack of literature on actor cooperation during the different phases of emergency planning, which could blind to its potential. There is a need to further explore the interactions, as well as collaboration and involvement of all actors. Also, perplexing was how little information related to cooperation or collaboration between different actors to prepare for crisis situations regarding water supply and sanitation in health care facilities was given in literature, although they are discussed in crisis response. The importance of considering water demands of hospitals and other health care facilities as part of a larger local and global disaster management has been emphasized by several authors across the board. However, the analysis did not yield any preparedness measures, i.e., formalizing plans or agreements between actors implementing regular meetings or installing dialogue formats and exchanges to raise awareness. Actors that should be involved in both preparedness and response according to literature are numerous and include state or private actors, as well as citizens, volunteers or patients with specific needs. Except for water suppliers when they are private enterprises, the private sector is not taken into consideration in the implemented preparedness measures, but only in response. Their involvement in the response was mentioned in Haiti, the United States, and Sri Lanka case studies (17, 35, 53).

This systematic review suggests that citizens and patients as actor groups across phases are hugely underrepresented in research, almost forgotten issue. Not much data is available on them, despite their direct vulnerability to water outages and their key role for both, preparedness and response. This raises the critical question of whether literature on water and health infrastructure tends to be more traditionalist, concerned with public actors and technical solutions, but blind to social and organizational concerns. In the event of a crisis, however, such aspects are of fundamental importance, as key actors responsible for functioning health care facilities can quickly become affected people who are themselves dependent on health care and who want to ensure the wellbeing of their families (39). Communication and awareness raising about the risks water supply outages for and across different actor groups is likewise hardly addressed beyond stressing the need.

Finally, a discrepancy was found between proposed preparedness as well as response measures and those implemented e.g., not many plans and communication with external stakeholders are mentioned in the actual preparedness, while the need is stressed all over. Another example is evacuation plans that do exist but that are not mentioned in preparedness, making actual preparedness partly difficult to assess. Many case studies reported the need to specifically improve water supply preparation, but the assessment of hospital preparedness is often limited to its overall evaluation, e.g., using hospital safety index (15, 26, 33). Health care facilities with reported preparedness and response mechanisms are mostly among the larger ones described, raising the question if smaller facilities are really less prepared or simply less researched and less often rescued during emergencies. There is a demand for studies covering the different phases, which would allow for assessing if a health-care facility was prepared for a specific event or rather for others, and how far preparedness helped in recovery.

One limitation of this study is that scientific literature might not provide a comprehensive overview on all preparedness and recovery plans, which might be covered more in gray literature or even be unpublished, depending on the country, if, for example, their publication is judged not to be conducive to the reputation of a private health care facility or simply its security. In other cases, health care facilities might have evacuation or other emergency plans which are not for water supply and sanitation problems only, but which might be activated in case of an outage. Another limitation is the underrepresentation of healthcare facilities other than hospitals and dialysis centers in literature. With respect to analysis, it was decided to only select and analyze such tools that were further described at least to a minimum.

Conclusions

This systematic review highlights the importance of water supply emergency preparedness in healthcare facilities, and lack of evidence on existing structures and mitigation mechanisms. In the context of rising climate change, health care facilities are, more than ever, vulnerable to natural hazard-induced disasters and ever-increasing fragilities. All involved actors, including particularly health care facilities, water suppliers and governmental authorities, must ensure that basic WASH services can be provided and can rapidly recover in the event of an emergency, and this is particularly important for reference hospitals, including health care facilities whose support is expected in the event of a disaster, providing first emergency response. This study yields multiple insights for future research on the provision of emergency water and sanitation services. Combining organizational and technical aspects, and intersecting theory and practice will be necessary to address existing gaps.

Future research should focus on identifying strategies to enhance infrastructure resilience, both through improving existing infrastructure and implementing new technologies. In addition to research on more technically oriented aspects, research is also needed on the appropriate identification, involvement and capacitation of all relevant stakeholders. Increasing capacity response and minimizing adverse effects on critical health infrastructure is key to maintaining public health and providing primary care.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

AC, SvdH, and SS contributed to conception and design of the study. SvdH and AC conducted the literature analysis and wrote the first draft of the manuscript. SvdH, AM, and AC compiled tables and figures. SS authored sections of the manuscript. All authors contributed to manuscript revision, editing, read, and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpubh.2022.1035212/full#supplementary-material

SUPPLEMENTARY TABLE 1
Search strategy for Medline and Web of Science database.

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Primary care for the urban poor in India during the pandemic: Uninterrupted management of non-communicable diseases and home-based care of patients with COVID-19 infection

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Problem: The two waves of COVID-19 severely affected the healthcare system in India. The government responded to the first wave with a strict nationwide lockdown which disrupted primary care, including the management of non-communicable diseases (NCDs). The second wave overwhelmed healthcare facilities leading to inadequate access to hospital services. Collectively, these issues required urgent responses, including the adaptation of primary care.

Approach: The Low-Cost Effective Care Unit (LCECU) of Christian Medical College, Vellore (CMC) has a network of community volunteers, community health workers, an outreach nurse, social workers and doctors who operate clinics in six poorer areas of Vellore. The network adapted quickly, responding to the lockdown during the first wave and ensuring ongoing primary care for patients with non-communicable diseases. During the second wave, the team developed a system in collaboration with other CMC departments to provide home-based care for patients with COVID-19.

Local setting: The LCECU is a 48-bed unit of the Department of Family Medicine, part of the 3,000-bed CMC. It originated in 1982, aiming to care for the poor populations of Vellore town. It has been actively working among urban communities since 2002, with a focus on delivering Community Oriented Primary Care (COPC), for six poor urban communities since 2016.

Relevant changes: During the first wave of COVID the LCECU team ensured patients with NCDs had uninterrupted primary care and medications by visiting them in their homes. The team also addressed food insecurity by organizing a daily lunch service for 600 people for over 2 months. In the second wave, the team responded to community needs by organizing and delivering home-based care to monitor patients affected by COVID-19.

Lessons learned: The COVID-19 pandemic raises many questions about the preparedness of health systems for disasters that disproportionately affect marginalized populations globally. COVID-19 is only one of the many potential disasters, including non-communicable diseases, mental health problems, pollution, climate change, and lifestyle illness. There is an urgent need to study models of care that support vulnerable communities in an accessible, cost-effective, and patient-oriented way, particularly in low- and middle-income countries. This paper outlines lessons on how the LCECU team addressed disaster management:

1. The COVID-19 pandemic has highlighted the importance of primary care-based rapid response interventions in disaster management.
2. The LCECU model demonstrated the effectiveness of a primary care intervention based on pre-existing networks and familiarity between primary care teams and the community.
3. Establishing community-based health care *via* interdisciplinary teams, including community health workers, community volunteers, outreach nurses, and doctors, is key.
4. Addressing other social determinants of health, such as food insecurity, is an important component of care delivery.

KEYWORDS

pandemic (COVID-19), urban poor communities, primary care, India, disaster response

Background

With nearly 31 million confirmed cases and more than 410,000 deaths due to COVID as of July 13th, 2021, India was struck hard by two waves of the COVID-19 pandemic (1). The Indian government responded to the first wave with a nationwide lockdown on March 25th, 2020, controlling the infection rate (2). The second wave started in the middle of March 2021. Tamil Nadu, in southern India, was one of the worst affected in the country, with nearly 250,000 cases and over 33,000 deaths as of July 14th, 2021 (3). The surge in patients in the second wave resulted in a complete state lockdown from May 4th, 2021 to July 19th, 2021. The city of Vellore, in Tamil Nadu, has a population of 186,000. Vellore had over 16,000 cases in the first wave. During the second wave, the Corporation area reported 300 new cases per day in May 2021. To control the spread, the Vellore City Municipal Corporation, the civic body that governs the city, converted 85 streets to "containment streets", blocking entry and exit of residents within barricades except for emergencies (4).

Problem

The pandemic brought forward two main challenges for primary care for the urban poor that necessitated urgent response and adaptation of services. First, was the need to provide ongoing continuity of care to patients with Non-Communicable Diseases (NCDs). Diabetes, hypertension, dyslipidemia, physical inactivity, and obesity are higher in the urban area of Vellore than in rural areas (5). Second was the management of those infected with COVID-19, particularly during the second wave, when it was necessary, to shift care to homes given the lack of hospital beds regionally and nationally.

Setting and intervention

The Christian Medical College, Vellore (CMC), a 3,000-bed institution spread over seven campuses with its motto "not to be ministered unto, but to minister", started the Low-Cost Effective Care Unit (LCECU) in 1982 to respond to the need of the urban poor. The LCECU is a 48-bed unit under the Department of Family Medicine. It provides highly subsidized, accessible, and affordable primary and secondary health care to the poor communities of Vellore. The LCECU built a network of Community Health Volunteers—originally trained through a Community Based Rehabilitation Project in 2002 (6)—and further developed with the LCECU in 2016 (to focus on Community Oriented Primary Care in six poor communities in Vellore targeting a population of 10,000 residents. The interdisciplinary team included community health workers (CHWs), an outreach nurse and social workers who collectively engaged with the community, including training community

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volunteers, and conducting home visits and weekly community clinics alongside family and community medicine physicians from the LCECU. Secondary-level care was provided in the base hospital of LCECU, and those who need tertiary care are referred to the CMC hospital for subsidized care.

Results

Response to the first wave

During the first wave, the focus was on ensuring that patients with NCDs received their routine medications. Through the work of the LCECU over the years, a registry of patients with chronic diseases in these communities was developed. The CHWs knew where patients lived, what medications they were on, and when their prescriptions needed refilling. Initially, CHWs went to patient homes, checked their patient-retained health record of their medications and organized prescriptions for the patients. The patients could then come and pick up the medications from the LCECU. However, when some areas were contained, and entry and exits were blocked, the community volunteers maintained communication with the CHWs over mobile phone and the prescriptions were given to volunteers who gave them to the patients. Networking with the volunteers also allowed the LCECU to remain aware of health issues in the community and rapidly respond to them. The volunteers alerted the unit to loss of jobs and lack of income in the community. People were struggling to access food, and this became an unprecedented need for the unit to respond to. Local individuals and groups supported the unit in providing lunch for about 600 people a day for more than 2 months. Had our resources been greater we may have been able to provide more meals or address other social factors that affected quality of life of our patients. The decades spent building relationships and developing community networks allowed our team to respond to the acute crisis caused by COVID lockdowns and restricted mobility.

Response to the second wave

As the second wave ravaged parts of India, various departments of the CMC coordinated and planned ways to mitigate the anticipated impact in Vellore. The program was called *UDHAVI* (meaning "help" in Tamil). It consisted of four areas: (1) triaging and providing telephone advice on COVID-19; (2) logistics that procured and distributed equipment (monitoring kits, oxygen concentrators, etc.); (3) counseling services for patients; and (4) home-based care for communities. When CMC learned that the local Indian Medical Association was planning similar telephone advice, we joined hands on the UDHAVI effort. This section describes the home-based care of the LCECU and its process.

Recruitment and training of community volunteers

LCECU held meetings in six service slum areas, explaining the need and plan for home-based care and recruiting community volunteers. The risk for volunteers was explained. Younger and vaccinated individuals were recruited. The LCECU provided COVID-related education and training on using the home-based care kits, which included pulse oximeters, thermometers, hand sanitizer and symptom monitoring sheets.

Identifying patients with COVID in the community

Patients were identified with the help of the volunteers by self-reporting and from the hospital lab database. Each patient who was eligible/opted for home-based care was met by the team, and one primary caregiver in the family was identified. The primary caregiver was taught to monitor the patient and complete the monitoring sheet. Caregivers contacted the CHW in their area twice daily with the monitoring data or sooner if red flags were noted. Families with smartphones and WhatsApp photographed the monitoring sheet and sent it to the CHW. However, the CHWs typically called the patients and their primary caregivers.

Home visits

The volunteers, CHWs, social workers and doctors visited patients daily. Follow-up was designed so that the volunteers would inform the doctors immediately if the patient needed escalated care. Otherwise, they reported a summary to the social worker who compiled the number of patients under care for discussion in the daily evening meeting. The team used WhatsApp for quick communication and coordination. The concept of confidentiality and shared confidentiality was explained and followed. The team documented findings and plans in the patient-retained charts, photographed it and then re-entered the same data on the electronic chart record by the next day at the base hospital. A few medical consultations with tertiary-level colleagues were held *via* phone. One cancer survivor with multiple co-morbidities who opted for home-based care, was given oxygen *via* concentrator, and visited daily in the home by the team. This included one visit by an internal medicine consultant and a respiratory technician. Though she passed away at home, the family was grateful for the palliative care provided and the opportunity to be with her during her last hours. This would not have been possible if she had been admitted to the hospital.

Review and planning meetings

The team met *via* Zoom daily to provide updates and discuss cases. Most of the patients cared for (34/37) required home-based care. One refused admission, one passed at home and one required admission for uncontrolled diabetes. Those needing medications such as inhaled budesonide, oral steroids, apixaban and supplemental oxygen were monitored by doctors directly as opposed to the CHWs. In addition to the care at home, the LCECU team secured funding through institutional fundraising efforts for patients needing admission at the main hospital for higher-level care.

The pandemic tested the network's resilience of community care programs the LCECU had built over the years and demonstrated the effectiveness of primary care based on community engagement and empowerment.

Ongoing care

LCECU was identified as one of the outreach centers of CMC for providing free vaccines to the community. Initially the vaccines were provided in the unit and later in the six outreach communities with the active involvement of the volunteers and a health team from the LCECU. The outreach clinics were restarted once the second wave subsided.

Discussion

One of the characteristics of a robust healthcare system is its ability to cope with sudden and unexpected health crises. The COVID-19 pandemic tested the tenacity of healthcare systems in every country in the world (7). Mortality was disproportionately higher in vulnerable populations, including the poor, elderly, migrants, minorities, and people living in densely populated areas. These groups have higher rates of NCDs, making them more vulnerable to COVID-19 infection and severe consequences of the disease and often fall through cracks in the healthcare systems (7–9). This article described how care of the urban poor in a city in southern India was adapted to meet the challenges of the pandemic. There were two major challenges that these communities faced during the pandemic; access to affordable, continuous care for those who had non-communicable diseases and a lack of hospital beds. Both required responses that deviated from the typical reactive hospital-based care model.

The lockdown and restricted movement of people could have had widespread implications for patients with chronic diseases had there not been an alternative arrangement to obtain regular care. The existing systems that LCECU had in place through its COPC program that blended public health with primary care acted as a safety net during this period. The network of volunteers, CHWs, outreach nurses, social workers and physicians caring for six defined vulnerable populations ensured that those who needed medical care received it, even during the strict lockdown. There were systems in place to identify those with chronic diseases requiring ongoing care and medications through home visits. Simultaneously, volunteers from the communities were constantly communicating with the CHWs in the team, alerting them to the urgent medical needs of community members. This went beyond the medical needs to address the social determinants of health. The LCECU played a key role in coordinating the supply meals to more than six hundred people for more than 2 months, when it became evident that many were struggling to eat due to loss of jobs and relatedly income.

The second wave of COVID infection overwhelmed the hospitals in Vellore. The poor from the town turned up at LCECU with fever, cough and shortness of breath. CMC had developed a system to help the communities around the institution. Using an interdisciplinary team-based approach, home care was provided for many patients. What enabled the LCECU team to quickly respond and deliver this unconventional method of care was their longstanding relationship with the communities. This was primarily due to the work of the CHWs and their engagement of volunteers from the communities. The LCECU had worked intensively in the six poor areas through their COPC program and built deep trust relationships over many years. The benefits of networks in care delivery, where the community is involved through its volunteers who are trained regularly to address the various needs, have been highlighted in several articles (10–12). Similarly, they highlight the importance of investing in relationships of trust with the community.

In general, there has been little published on existing models of care for the management of NCDs during COVID-19 or other disasters. However, the integration of CHW's as key players in emergency responses is being advocated globally (13). Similar to the LCECU example, the community health clinic program in Bangladesh found that CHW's made significant contributions ensuring essential health services continued during the COVID-19 pandemic (14).

The steps taken by LCECU in actively reaching out to the six areas with visits by various members of the outreach teams and starting outreach clinics, prepared the ground for rapid and effective responses when the pandemic hit them. This reiterates the need for responses to disasters that are based in primary care and emphasizes the important role of interdisciplinary teams and community engagement.

Conclusions

The COVID-19 pandemic raises many questions about the preparedness of health systems for disasters that affect all sections of people globally. COVID-19 is one of the many disasters affecting people worldwide, including non-communicable diseases, mental health problems, pollution, and climate change. There is an urgent need to study models of care that can address these in an accessible and cost-effective manner, especially in low- and middle-income countries. This paper highlights: (1) the critical role primary care plays in responding to disasters; (2) the effectiveness of interdisciplinary team-based primary care; (3) the benefits of a COPC model of care based on community engagement and building networks and familiarity between primary care staff and community volunteers; and (4) the important role of addressing the social determinants of health.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

SA led the strategic planning exercise for restricting the outreach and community services of LCECU through Community Oriented Primary Care, gave leadership to the follow up of non-communicable diseases during the pandemic, and contributed to the manuscript. SJ led the care of patients during the second wave including putting systems in place of home based care and contributed to the preparation of the manuscript. AG involved in discussions about the manuscript, made corrections, and changes to the drafts. SB contributed significantly to preparation of the manuscript and finalize the words used to describe the response to the disaster. MK made significant contribution to writing the manuscript. PM and AF involved in the ground work of the response including home visits and follow up of patients with COVID-19. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Effectiveness of the graded transport mode for the intrahospital transport of critically ill patients: A retrospective study

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Aim: The purpose of this study was to evaluate the effectiveness of the graded transport mode in the intrahospital transport (IHT) of critically ill patients.

Methods: This is a retrospective study, including 800 patients and categorized them into control and observation groups. The control group included 420 critically ill patients who were transported *via* conventional methods from our emergency resuscitation unit from June 2017 to December 2017. The observation group included 380 critically ill patients who were transported through a graded transport mode from January 2018 to June 2018. We performed intergroup comparisons of the incidence rates and causes of adverse events (AEs), transport time, length of stay, and mortality rate.

Results: The observation group had significantly lower transport time and AE incidence rates than the control group. However, no significant differences were observed in terms of the length of stay and mortality rate between the two groups.

Conclusion: The most notable merits of the graded transport mode in the IHT of critical care patients include the fact that it significantly reduces the incidence of AEs during IHT, shortens the transport time, and improves transport efficiency, thereby ensuring the safety of critically ill patients.

KEYWORDS

emergency treatment, critically ill patients, intrahospital transport, adverse events, graded transport

Introduction

The emergency resuscitation room is the first admission unit for critically ill patients; patients whose condition does not improve after the initial evaluation and resuscitation need to be transported to appropriate departments for further diagnosis, examination, treatment, and hospitalization, known as intrahospital transport (IHT) (1). IHT exposes patients to a mobile environment and increases their susceptibility to the occurrence of adverse events (AEs). Severe AEs can exacerbate diseases and even endanger patient lives and are associated with significant mortality and increased healthcare costs. To ensure the timeliness and safety of IHT for these patients, standardization and optimization of the IHT process are urgently required (2, 3).

In recent years, graded transport mode, as a new IHT method, has been widely applied in Chinese hospitals. According to the severity of patients, the graded transport mode divides IHT into three risk levels, namely Grade I (high risk), Grade II (medium risk), and Grade III (low risk). However, the differences in transport time, length of hospital stay, and mortality between graded transport mode and traditional transport mode remain unknown.

In this study, we developed a new set of quality standards for IHT in critically ill patients. We aimed to explore whether the graded transport mode can effectively reduce the incidence of IHT related adverse events, shorten transport time and improve transport efficiency.

Methods

Sample sources

We collected critically ill patients admitted to the emergency department of our hospital from June 2017 to June 2018 and divided them into graded transport and traditional transport. We selected patients according to the following inclusion criteria: (1) critically ill patients admitted to the emergency resuscitation room requiring IHT owing to the need for CT and other imaging examinations, emergency interventions, emergency surgery, and hospitalization; (2) age > 18 years; (3) signed informed consent for the risk of transport obtained from the families of all patients; and (4) complete medical records. Exclusion criteria were pregnancy, infectious disease, hospital transfer, and patients with missing values.

IHT modes

Patients in the control group received conventional transport. After the attending physician assessed the patients' condition and permitted the transport, the families of the patients were involved in the transport process. In addition, emergency nurses and physicians carried respiratory support, resuscitation supplies, cardiac monitors, and other facilities for assistance.

Patients in the observation group received the graded transport. The steps of graded transport are as follows: (1) evaluation of transport risk grading: the transport risk grading is determined according to the patient's condition classification standard, and the corresponding medical staff, instruments, equipment and drugs are allocated according to different risk levels. Classification criteria are mainly referred to Vital Signs, Glasgow Coma Scale (GCS) score for consciousness state, Respiratory support, Circular support and primary clinical symptoms; (2) preparation before transport: the nurse in charge of transport must check the patient's physical status, equipment, drugs, etc., and fill in the form for graded transport; (3) transport: during the transport, the patient's physical condition and condition change must be observed at all times, ensure the safe placement and normal operation of medical equipment, prepare for emergency treatment, and try to avoid the occurrence of adverse events in transport; and (4) end of transport: the nurse in charge of transfer shall evaluate the situation of the patient after transfer and record the relevant contents of graded transport. Finally, the doctor in charge of the transfer and the doctor of the department receiving the patient jointly confirm the completion of the whole transfer process. Transport risk was categorized into Grades I, II, and III (from high to low), and the specific measures are presented in Tables 1, 2.

Observational indicators

In both groups, the average transport time was calculated from the time the patients were transferred from the emergency resuscitation room by the medical staff till they returned to the hospital bed (or arrived at the relevant inpatient unit) after the examination or treatment was completed. The transport time only included the time spent during the transport process, excluding the examination, treatment, and patient handover processes. In addition, we performed intergroup comparisons of the incidence of AEs related to IHT, including the AEs related to the disease (sudden change of consciousness, increase or decrease in heart rate or blood pressure by > 20%, decrease of peripheral oxygen saturation by > 20 or < 90%, sudden cardiac arrest, and massive hemorrhage), personnel (tube dislodgement, displacement, and communication between the teams), and apparatus and drugs (apparatus malfunction [oxygen/respirator failure, black screen, inadequate battery level, non-inflatable cuff, and other technical problems] and inadequate preparation of drugs). Finally, the total length of stay and 30-day intrahospital mortality were compared between the two groups.

Statistical analysis

IBM SPSS version 25.0 was used for data analyses. Measurements conforming to normal distribution were expressed as mean ± standard deviation ($x \pm SD$). An independent samples *t*-test was used to perform intergroup comparisons of the means. Enumeration data were expressed as percentages. In addition, two rates or constituent ratios were compared using the chi-square test, and ranked data were compared using the rank-sum test for multiple ratios. $P < 0.05$ indicated a significant difference.

Results

Demographic characteristics

The critically ill patients transported *via* conventional methods (control group) were collected from June 2017 to December 2017 ($n = 420$; mean age, 66.23 ± 19.64 [range, 18–92] years). The observation group included critically ill patients who were transported *via* graded transport from January 2018 to June 2018 ($n = 380$; mean age, 65.45 ± 20.37 [range, 18–94] years). The control group comprised 92, 71, 63, 46, 65, and 83 patients with neurological diseases, cardiovascular diseases, respiratory diseases, digestive system diseases, trauma, and other diseases, respectively. There were 79, 68, 60, 54, 63, and 56 patients with neurological diseases, cardiovascular diseases, respiratory diseases, digestive system diseases, trauma, and other diseases in the observation group, respectively. In addition, no significant intergroup difference was observed in the general information ($P > 0.05$) (Table 3).

IHT time of critically ill patients

The IHT time of patients in the observation group from the emergency department to CT/MRI examination, interventional

TABLE 1 Specific measures related to intrahospital transport for critically ill patients in the control and observation groups.

Measures	Control group (June 2017 to December 2017)	Observation group (January 2018 to June 2018)
Transport training	(1) Maintenance of transport-related apparatus and equipment; (2) Ensuring the presence of an emergency plan for cardiac arrest, accidental extubation of artificial airway, malfunction of the ventilator during transport, and insufficient oxygen source; (3) Three theoretical lectures on cardiopulmonary resuscitation (CPR) operation during transfer and team first aid; (4) Nurses and physicians are required to have worked in emergency medicine for more than 1 year and 6 months, respectively. In addition, they are required to attend training and qualify in the theoretical, CPR, and IHT simulation tests in emergency medicine before they can be deemed independent in performing IHT for critically ill patients	(1) In addition to the traditional training methods, ensuring the inclusion of special safety inspection training modules including the DSA safety instruction, enhanced CT safety instruction, and hyperbaric oxygen safety instructions; (2) Emphasis on training on the use of transport vehicles, apparatus, and drugs (all participants need to qualify in the examination); (3) Emphasis on the transport mode in the status, background, assessment, and recommendations
Risk grading	Comprehensive assessment of vital signs by the attending physician	Grades I, II, and III (Table 2)
Logistical support	Dedicated transport elevators equipped with a dedicated operating staff	(1) Relatively fixed transport logistics staff are trained; (2) The number of transport elevators is increased each building is installed with a dedicated elevator for transport; ensuring that elevator staff members wear identification badges, carry wireless intercom to contact in advance to prepare for transport, and possess excellent service attitudes; (3) Emergency drills for safe transport are regularly performed
Communication and cooperation	Routine telephone communication between medical and nursing staff and relevant departments	(1) Efficient communication between the physician and the examining department to reduce waiting time. (2) Health education and psychological care by nurses to calm anxious family members of patients; (3) Transport operation by experienced medical personnel; (4) Radiological examination report should be issued within 15 min (examination report for special patients should be issued immediately); (5) Verification of patient, drug, and catheter information by medical personnel when handing over patients to other departments
Quality control analysis	Quarterly quality control analysis of the pertinent problems, adjustments, and improvements	(1) Lectures are conducted to train medical staff to identify the disease etiologies; (2) Transport defect analysis for critically ill patients is performed once a month (defects were analyzed using a simple root cause analysis method to reduce risk)

room, surgery room, ICU ward, and general wards was significantly lesser than that of patients in the control group ($P < 0.05$) (Table 4).

Incidence of AEs during the IHT of critically ill patients

One hundred patients in the control group developed AEs during transport (AE incidence rate, 23.81%). In addition, 43 patients in the observation group developed AEs during transport (AE incidence rate, 11.32%). Therefore, there was a significant intergroup difference in the AE incidence ($P < 0.05$). In the control group, the incidence rates of disease-, personnel-, apparatus-, and drug-related AEs were 8.81, 5.71, 5, and 4.29%, respectively, whereas the incidence rates for patients in the observation group were 4.73, 2.63, 2.11, and 1.84%, respectively; both groups showed significant intergroup differences ($P < 0.05$) (Table 5).

Length of stay and 30-day intrahospital mortality rate

The total lengths of stay of patients in the observation and control groups were 19.63 ± 13.95 and 19.18 ± 13.58 days, respectively. Furthermore, the 30-day intrahospital mortality rates were 16.58 and 17.62%, respectively, in the two groups (Table 6). There were no significant intergroup differences in terms of the length of stay and 30-day mortality ($P > 0.05$).

Discussion

IHT is a crucial and unavoidable step for critically ill patients to receive further diagnosis and treatment. However, such patients are susceptible to significant changes during IHT owing to reasons related to disease progression, apparatus used, medications, and transport personnel, which may cause serious complications and could even result in mortality (4). Findings of a recent meta-analysis indicated that critically ill patients may develop AEs during IHT, with a 26.2% incidence rate of mild-to-moderate AEs but a relatively low incidence rate of severe AEs (5). This meta-analysis facilitated a risk-benefit analysis of the diagnostic or therapeutic procedures for critically ill patients requiring IHT. In addition, the incidence rate of AEs was reportedly as high as 79.8% in a study on 441 patients admitted to the ICU undergoing IHT (6). Effective care during IHT is a challenge (7, 8). Owing to the high demand for emergency transport and the exposure to the patient's family during the transport process, medical disputes frequently occur, which places a considerable burden on transport physicians and nurses (9). Consequently, improving the safety of IHT is an area of great interest in research. Overall, meticulous transport planning and procedures,

TABLE 2 Transport risk grading.

Evaluation items	Grade I	Grade II	Grade III
Vital signs	Unstable	Relatively stable with life support	Stable without life support
Glasgow Coma Scale (GCS) score for consciousness state	Deep coma (GCS score < 9)	Moderate coma (GCS score of 9–12)	No coma or light coma (GCS score > 12)
Respiratory support	Artificial airway with high respiratory support conditions (PEEP $\geq$ 8 cm H_2O and $FiO_2 \geq 60\%$)	Artificial airway with poor respiratory support conditions (PEEP < 8 cm H_2O and $FiO_2 < 60\%$)	Autonomous expectoration without artificial airway support
Circular support	Pumping of $\geq$ two vasoactive drugs	Pumping of $\geq$ one vasoactive drugs	No vasoactive drugs required
Primary clinical symptoms	Acute myocardial infarction, severe arrhythmia, severe dyspnea, recurrent convulsions, fatal trauma, and arterial dissection	ECG-suspected myocardial infarction, non-COPD patients with pulse oxygen of <90%, surgical acute abdomen, severe headache, and severe persistent hyperthermia	Chronic diseases
Medical and nursing staffing	Two physicians and two nurses	One physician and two nurses	One physician and one nurse
Apparatus and drugs	Apparatus: two bottles of oxygen, transport monitor, transport ventilator, oropharyngeal airway, micropump, automated external defibrillator (AED), portable sputum aspirator, intubation supplies, and puncture supplies	Apparatus: one bottle of oxygen, transport monitor, simple ventilator, oropharyngeal ventilator, micropump, AED, and puncture supplies	Apparatus: one bottle of oxygen, handheld pulse oximeter, simple respirator, and puncture supplies
	Drugs: epinephrine, dopamine, amiodarone, midazolam, lidocaine, and atropine	Drugs: epinephrine, midazolam, and saline	Drug: saline

TABLE 3 Baseline characteristics of patients.

	Control group (n = 420)	Observation group (n = 380)	P-value
Gender			0.83
Male	244 (58.1%)	224 (58.9%)	
Female	176 (41.9%)	156 (41.1%)	
Age	66.23 ± 19.64	65.45 ± 20.37	0.56
Diseases			0.37
Neurological diseases	92 (21.9%)	79 (20.8%)	
Cardiovascular diseases	71 (16.9%)	68 (17.9%)	
Respiratory diseases	63 (15.0%)	60 (15.8%)	
Digestive system diseases	46 (11.0%)	54 (14.2%)	
Trauma	65 (15.5%)	63 (16.6%)	
Other diseases	83 (19.8%)	56 (14.7%)	
Mortality	74 (17.6%)	63 (16.6%)	0.70

well-performing transport equipment, and well-trained professional teams are necessary to ensure the safety of critically ill patients during transport and reduce the incidence rate of AEs, thereby facilitating the treatment of patients (10–13).

The results of the present study suggested that the IHT time of patients in the observation group from the emergency department to CT/MRI examination, interventional room, surgery room, ICU ward, and the general ward was significantly shorter than that of patients in the control group. This phenomenon could be attributable to the following factors: First, the dedicated transport elevator and staff reduced the waiting time for the elevator; second, transport risk grading allowed medical staff to prepare supplies rapidly and reduce omissions; third, rational manpower allocation and collaboration of medical and nursing teams improved the transport efficiency (14); fourth, communication with medical and technical departments before transport reduced unnecessary waiting time; fifth, changes in the perceptions of medical and technical staff and pre-transport examination of critically ill patients by experienced technicians shortened the transport time. These factors reduced the stress and anxiety of patients and their families and saved the time of medical staff. Furthermore, the reduced waiting time alleviated the lack of oxygen storage, which reduced AEs caused by the low battery level of the monitor and ventilator.

In the present study, the incidence rates of AEs during ITH showed significant intergroup differences, i.e., 23.81 and 11.32% for the control and the observation groups, respectively. In addition, the incidence rate of AEs related to personnel, apparatus, and environment (or hidden problems) was significantly lower in the

TABLE 4 Incidence of adverse events (AEs) in the observation and control groups.

Groups	Disease-related AEs	Personnel-related AEs	Apparatus-related AEs	Drug-related AEs
Observation group ($n = 380$)	18 (4.73%)	10 (2.63%)	8 (2.11%)	7 (1.84%)
Control group ($n = 420$)	37 (8.81%)	24 (5.71%)	21 (5%)	18 (4.29%)
x^2	5.1685	4.6589	4.7851	3.9350
P-value	0.0230	0.0309	0.0278	0.0473

TABLE 5 Intrahospital transport time of patients in the observation and control groups.

Groups	CT/MRI examination (n)/time (min)	Intervention room (n)/time (min)	Operating room (n)/time (min)	ICU (n)/time (min)	General ward (n)/time (min)
Observation group	312/15.64 ± 4.87	42/12.45 ± 2.98	42/14.67 ± 3.54	153/14.89 ± 4.22	227/15.81 ± 5.33
Control group	383/17.83 ± 5.27	49/14.14 ± 3.21	47/16.13 ± 2.82	168/15.96 ± 3.81	252/17.40 ± 5.15
T-value	5.6194	2.5856	2.1652	2.3990	3.3195
P-value	2.17E-08	0.0113	0.0331	0.0170	0.0010

TABLE 6 Length of stay and 30-day intrahospital mortality in the observation and control groups.

Groups	Total length of stay (day)	30-day intrahospital mortality
Observation group ($n = 380$)	19.63 ± 13.95	16.58% (63)
Control group ($n = 420$)	19.18 ± 13.58	17.62% (74)
t/x^2	0.4547	0.1521
P-value	0.6494	0.6965

observation group than in the control group. This phenomenon may be attributed to the following factors. First, after defining and classifying AEs, we changed the perceptions of medical and technical personnel. After realizing the importance of the safety of IHT in the treatment of critically ill patients, the medical and nursing staff carefully evaluated the patients before transport, provided considerable attention to the associated details, and strengthened the assessment of all aspects of the process, which reduced the incidence rate of disease-related AEs. In addition, the selection and use of a graded transport list greatly reduced the lack of pre-transport materials. Furthermore, after theoretical training, operational training, objective structured examinations, and monthly quality control improvements, the medical personnel were calm, prepared, and skilled in the face of emergencies and could appropriately and promptly handle changes related to specific conditions, thereby reducing the incidence rate of personnel-related AEs. Finally, the provision of dedicated transport elevators and operating personnel reduced the unnecessary waiting time, transport time, and power consumption by hypoxia monitors and ventilators, thereby reducing the incidence rate of the environment- and apparatus-related AEs (11).

Studies on the relationship between IHT and the length of stay and mortality in critically ill patients have reported inconsistent findings. Several studies have demonstrated the correlation of the number of IHTs with delirium, length of stay, and mortality (15–17). Meanwhile, Erika et al. (18) observed no significant impact of IHT-related AEs on patient hospitalization. Despite the absence of any significant intergroup differences in terms of the impact of IHT-related AEs on the length of stay and mortality, further measures should be implemented to reduce these adverse factors.

A graded transport model can significantly improve transport efficiency, shorten transport time, and reduce the incidence rate of AEs during the transport process. This mode is a successful innovation in emergency medicine as it can reasonably optimize the allocation of emergency medical resources and improve the safety and efficiency of IHT. Unlike previously used transport modes, the graded transport mode contributes to the establishment of a safe and efficient IHT system for emergency patients. Different transport modes can be applied to corresponding levels of transport to achieve rationalization and safety of medical resource allocation. In addition, effective assessment and grading of the risk of patient transport and prompt preparation according to the actual situation can aid the reasonable allocation of medical resources and further improve the safety of transport, thereby enabling better treatment of critically ill patients.

Limitations

This study has some limitations. First, the sample size of this study was relatively small. In addition, the retrospective nature of this study may have led to bias in patient selection. Moreover, we could not conduct a survey on the satisfaction of patients and the receiving departments owing to the specificity of the emergency setting. Finally, patient hospitalization costs could not be analyzed in comparative studies. Consequently, further studies are warranted to validate our findings.

Conclusion

In summary, the graded transport mode has a unique value in clinical settings. It can effectively improve the safety of transport and reduce the incidence of AEs. As a result, vital signs of patients at all risk grades can be effectively maintained during the transport process. Although no significant intergroup differences were observed in terms of the length of stay and 30-day mortality, the graded transport mode can shorten the IHT time of critically ill patients and reduce the AE incidence rates.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving human participants were reviewed and approved by the study was approved by the Ethics Committee of Kunshan Hospital Jiangsu University (Kunshan, China). The patients/participants provided their written informed consent to participate in this study.

Author contributions

JM and LL conceived, designed, and coordinated the study. LL, JM, and ZG drafted this manuscript. XX, HY, CZ, SL, and JM were responsible for collecting and measuring the imaging data. LL, CZ, XX, and SL were responsible for collecting clinical data. JM and ZG were responsible for data analysis. All authors read, approved, and contributed to the final manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Robust optimization for casualty scheduling considering injury deterioration and point-edge mixed failures in early stage of post-earthquake relief

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Objective: Scientifically organizing emergency rescue activities to reduce mortality in the early stage of earthquakes.

Methods: A robust casualty scheduling problem to reduce the total expected death probability of the casualties is studied by considering scenarios of disrupted medical points and routes. The problem is described as a 0-1 mixed integer nonlinear programming model. An improved particle swarm optimization (PSO) algorithm is introduced to solve the model. A case study of the Lushan earthquake in China is conducted to verify the feasibility and effectiveness of the model and algorithm.

Results: The results show that the proposed PSO algorithm is superior to the compared genetic algorithm, immune optimization algorithm, and differential evolution algorithm. The optimization results are still robust and reliable even if some medical points fail and routes are disrupted in affected areas when considering point-edge mixed failure scenarios.

Conclusion: Decision makers can balance casualty treatment and system reliability based on the degree of risk preference considering the uncertainty of casualties, to achieve the optimal casualty scheduling effect.

KEYWORDS

emergency logistics, the injury worsened, facility disruption, robust optimization, particle swarm optimization

1. Introduction

Earthquakes often occur randomly without warning and bring devasting damages to affected areas. Earthquakes not only cause serious economic losses but also lead to many people's injuries or even death (1, 2). Statistically, the 1976 Tangshan earthquake caused 242,769 deaths and 435,556 injuries. The 2008 Wenchuan earthquake killed 69,227 people, injured 374,643 people, and left 17,923 people missing. After a large-scale destructive earthquake, the number of casualties increases rapidly, the injury states are complicated, and the affected areas are wide. The scientific and effective treatment of the casualties is the primary task of the post-disaster relief work, and its efficiency is related to the success or failure of the post-disaster rescue. Especially the early stage of post-earthquake relief is the critical period for emergency rescue and disaster relief (3). How to organize rescue activities plays a crucial role during this golden rescue period, such as transporting and treating the casualties (4). Consequently, utilizing existing medical resources to build an efficient and reliable emergency logistics network to transport the casualties to medical points efficiently for treatment is an urgent problem to be resolved in the early post-earthquake period.

The problem of casualty transportation scheduling was usually described as an emergency facility location-allocation problem or a delivery vehicle routing problem (5–8). On this basis, some studies considered the type of casualties (9, 10) or the deterioration of the wounded (11) to further optimize the casualty scheduling. However, the above literature generally contained an implicit assumption that the facility was completely reliable without disruption. This assumption did not correspond to reality. Especially in the post-earthquake emergency logistics system, the facilities and routings are easy to fail due to the impact of earthquake disasters and their secondary disasters. The disruption factors were considered in some literature (12–14).

To sum up, researchers have carried out in-depth research on the optimization of emergency scheduling for casualty transportation after earthquake disasters, but there are still some problems that are required further study. Firstly, most of the existing research studied the problem of injury deterioration and casualty scheduling alone without considering the two problems simultaneously. Secondly, most of the current studies assumed that the road and facilities in the earthquake disaster logistics network were completely reliable without failures. Although some literature considered road disruption or facility failures, there are few works considering the mixed failure state of points (facility) and edges (route) in the emergency logistics network simultaneously. Thirdly, existing studies usually assumed that information such as the number of casualties was determined or described as fuzzy parameters. In reality, such a number cannot be estimated exactly. To fill up this gap, this paper considers the point-edge mixed failure scenario, combines the evolution of injury situation, adopts the robust optimization method to deal with the uncertain amounts of casualties, and further studies the optimization problem of casualty transport scheduling in the early stage of post-earthquake relief.

The main differences between this paper and previous studies are summarized in Table 1. More specifically, the contributions of this paper are as follows. (1) We propose a new casualty scheduling robust optimization problem for post-earthquake relief. As mentioned in the previous subsection, the proposed problem considers some new characteristics in the early stage of post-earthquake relief, such as point-edge mixed failure scenarios, injury deterioration, and multiple transportation modes. (2) A mixed integer non-linear programming (MINP) model is established to formulate the proposed problem. (3) According to the characteristics of the model, an improved integer-encoded particle swarm optimization (PSO) algorithm is designed in this paper. The improved PSO is compared with the genetic algorithm (GA), immune algorithm (IA), and differential evolution algorithm (DE).

2. Literature review

This section will review relevant literature in the following three categories.

2.1. Traditional casualty scheduling problems

The problem of casualty transportation scheduling is usually described as an emergency facility location-allocation problem or a delivery vehicle routing problem (5–8). Mansoori et al. (15) proposed a multi-objective humanitarian supply chain design problem that minimizes the total number of injured not transferred to hospitals. Fiedrich et al. (26) proposed a dynamic optimization model where the total number of fatalities during the initial search-and-rescue period after strong earthquakes is minimized. Andersson et al. (27) established a support tool for dynamic ambulance relocation and automatic ambulance dispatching. Xie et al. (28) formulated a lane-based evacuation network optimization problem that integrates lane reversal and crossing elimination strategies. A Lagrangian relaxation algorithm based on the principles of Tabu search is designed to solve the model. Mclay et al. (29) proposed an improved Markov decision model to optimize ambulance dispatch dynamically to maximize the number of critically injured patients. Knyazkov et al. (30) studied the present situation of emergency transport for patients with acute coronary heart disease in St. Petersburg. The optimization of ambulance routes was proposed according to the road network in the city, to improve the number of ambulances per capita and the speed of ambulance response in this work. Sung et al. (31) transformed the problem of treating the injured after a disaster into the dispatching problem of emergency ambulances with the goal of maximizing the expected survival rate and designed a column generation algorithm. Repoussis et al. (32) proposed a mixed integer programming formulation for the combined ambulance dispatching, patient-to-hospital assignment, and treatment ordering problem. The objectives are to minimize the overall response time and the total flow time required to treat all patients. Shavarani et al. (33) described how to properly allocate existing emergency vehicles to hospitals and effectively plan vehicle routes after a disaster in a densely populated area, to maximize patient survival. Sun et al. (16) proposed an emergency model of the location-transportation-allocation problem. The objective is to minimize the total cost and the sum of injury severity scores. The integrated research on the problem of casualty scheduling and emergency facility location is studied in some literature (34, 35). Sheu et al. (36) proposed a method for designing a seamless centralized emergency supply network. A three-stage multi-objective (travel distance minimization, operational cost minimization, and psychological cost minimization) mixed-integer linear programming model is built to describe the problem. Hu et al. (37) proposed a mixed integer programming model that considers the uncertainty of the number of injured people and integrates the decision of locating shelters and transferring injured people. Chou et al. (17) proposed a patient transportation and assignment model considering the routing of ambulances and operational conditions of hospitals.

2.2. Casualty scheduling problems considering wounded types

A large number of wounded personnel emerged in the early stage after an earthquake, thus it is important to dispatch the wounded personnel considering the wounded type (9, 10). Caunhye et al. (18) constructed a three-stage stochastic programming model to locate alternative care facilities and allocate casualties.

TABLE 1 Summary of relevant research.

Reference	Road disruption	Facility disruption	Parameter uncertainty	Casualty triage	Injury deterioration	Multi-transportation modes	Solution method	Modeling approach
Bronfman et al. (2)	No	No	No	Yes	Yes	No	CPLEX	MILP
Mansoori et al. (15)	No	No	Robust	No	No	No	CPLEX	MINP
Sun et al. (16)	No	No	Robust	Yes	Yes	Yes	CPLEX	MILP
Chou et al. (17)	No	No	No	No	No	No	Heuristic	MINP
Caunhye et al. (18)	No	No	Stochastic	Yes	No	No	Heuristic	MINP
Ghasemi et al. (19)	No	No	Stochastic	Yes	No	No	Heuristic	MINP
Caglayan et al. (20)	No	No	No	Yes	No	No	CPLEX	MINP
Vahdani et al. (21)	No	No	Robust	Yes	No	Yes	GAMS	MILP
Zeng et al. (22)	No	No	No	Yes	No	No	Heuristic	MILP
Cheng et al. (23)	Yes	Yes	Stochastic	No	No	No	Heuristic	MINP
Sun et al. (24)	No	Yes	Robust	Yes	No	No	CPLEX	MILP
Desi-Nezhad et al. (25)	Yes	No	Stochastic	No	No	Yes	GAMS and CPLEX	MILP
Our study	Yes	Yes	Robust	Yes	Yes	Yes	Heuristic	MINP

MILP, Mixed integer linear programming.

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The model integrates casualty triage and the movement of self-evacuees. Ghasemi et al. (19) proposed a stochastic multi-objective mixed-integer mathematical programming for logistic distribution and evacuation planning during an earthquake. Na et al. (38) classified the wounded according to the results of the field diagnosis of the wounded, combined with the medical resources required by different wounded, assigned rescue vehicles to the wounded, and established a mixed integer linear programming model with cost minimization as the objective function. Talarico et al. (39) classified the injured into two categories: those that can be treated at local sites and those that must be treated in hospitals. They established an optimization model of ambulance routing decisions, aiming at minimizing the weighted waiting time of the injured, and solved the model with a large-scale neighborhood search algorithm. Rezapour et al. (40) divided the injured in each disaster area into yellow and red grades and studied how to reasonably allocate search and rescue personnel and medical personnel to the disaster area. More studies are available in literature (41, 42). The condition of the wounded deteriorates over time in reality. Wilson et al. (43) proposed a Markov chain model for the injury state transfer of casualties. Jin et al. (11) proposed an optimization model for patient delivery and medical resource allocation with capacity restrictions considering the severity of injuries. Liu et al. (44) set up a double objective optimization model for temporary medical service point location and the optimal medical service allocation decisions considering the deterioration of injury. The goals are to maximize the expected number of survival and minimize the total operation cost.

2.3. Casualty scheduling problems considering disruptions

The facilities (points) and the roads (edges) of an emergency logistics network might be disrupted after a large-scale earthquake. The logistics network design problem considering facility failures is studied in some literature. Bayram et al. (45) studied the shelter location and evacuation route assignment problem considering the disruption/degradation of the evacuation road network structure. Cheng et al. (23) adopted a two-stage robust optimization framework to study the robust fixed cost location problem in the case of uncertain demand and facility disruption, and developed a column constraint generation algorithm to accurately solve the model. Zhou et al. (46) constructed a location-allocation model for emergency facilities suitable for the initial stage of post-earthquake rescue, considering facility disruption and multiple types of fuzzy demand. Mohammadi et al. (47) studied a multi-objective reliable optimization model to organize a humanitarian relief chain. They made a broad range of decisions, including reliable facility location-allocation, fair distribution of relief items, assignment of victims, and routing of trucks. Sun et al. (24) proposed a scenario-based robust dual-objective optimization model to study the location of medical facilities, casualty transport, and relief material distribution under the temporary medical point failure scenarios. There are also some studies on the design of emergency logistics networks considering edge (road network) failures. Sabouhi et al. (48) proposed a comprehensive stochastic programming model for the distribution of relief materials in disaster areas, taking the demand and disrupted roads as uncertain parameters. Gong et al. (49) studied the decision optimization of patient scheduling in the early stage of post-earthquake rescue, considering the factors such as the deterioration of the injured and road disruption. Desi-Nezhad et al. (25) developed a two-stage stochastic programming model to transport injured people with consideration of multiple disruptions at transportation links and facilities.

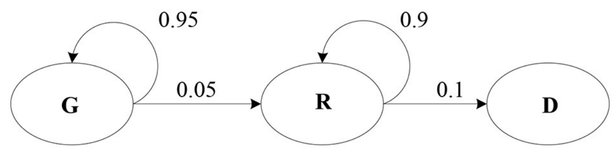

FIGURE 1
Random evolution process of the injury state.

3. Description of injury deterioration

The injury deterioration can be described by a Markov chain proposed by Wilson et al. (43). The injury state of the wounded evolves toward the direction of gradual aggravation or continues to maintain the original state, with a certain probability in the process of waiting for rescue. And death is the end of the injury evolution in process. If the injury at the current stage is severe, the injury may be transferred to the death state or remain severe if effective treatment is not available at the next stage. If the injury is minor at the current stage, the injury may be transferred to severe or remain minor if no rescue is available at the next stage. It can be seen from the evolution of the injury state that the state transfer is stochastic, and the state of the wounded at the next stage only depends on the current state independent of the historical state, which is consistent with the no aftereffect of the Markov process. Therefore, the evolution of the injury has a Markov character.

In this paper, the evolution process of injury is divided into three finite-state Markov processes: minor injury (Green, G), severe injury (Red, R), and death (D). The process is repeated until the casualty dies or is saved. Let the initial time $t = 0$. All rescue teams are ready at the initial time. The injury level of the casualty is randomly and unidirectionally changed once per minute without any medical treatment, as shown in Figure 1.

It is assumed that there is a linear relationship between the severity of injury and the time before the wounded is treated. According to the random transfer probability between the injury states, the possible death probability of the casualty j whose initial injury state is R is expressed as formula (1).

$$P_r^D(T_{ij}^r, L_r) = p_{rd} T_{ij}^r \quad (1)$$

In expression (1), T_{ij}^r indicates the time required to transport a severe casualty from the affected point i to the medical point j. L_r represents the injury state of the casualty in the initial time is r. p_{rd} indicates the probability that a casualty's injury state changes from severe to death and let $p_{rd} = 0.1$ in this article referring to literature (43).

If $p_{rd}T_{ij}^{r} > 1$, the wounded may die in a waiting process. The death probability of the severe casualty while waiting for rescue can be expressed by Equation (2).

$$P_r^D(T_{ij}^r,\ L_r) = \min\left(1,\ p_{rd}T_{ij}^r\right) \tag{2}$$

The death probability of the minor casualty can be written by the transition probability equation. That is, the probability of changing from a minor injury to a severe injury is calculated first, and then the probability of deteriorating from the severe injury to death is calculated. The time T that the wounded fully evolves from G to R should be first judged when calculating the death probability. According to Figure 1, the transition probability from state G to R is 0.05. Let $0.05^*T = 1$, then, $T = 20$ when G evolves into R. When the ambulance arrival time is <20 units, the wounded does not evolve to death, and the death probability is 0. When the arrival time of the ambulance is >20 units, the death probability in this state is $P_g^D(T_{ij}^g,\ L_g) = \min\left(1,\ p_{rd}(T_{ij}^g - T)\right)$. So, the probability function of death in a minor state is a time-segment function, see expression (3).

$$P_g^D(T_{ij}^g, L_g) = \begin{cases} 0, & 0 < T_{ij}^g \le T \\ \min\left(1, p_{rd}(T_{ij}^g - T)\right), & T_{ij}^g > T \end{cases} \tag{3}$$

Therefore, the death probability functional of a casualty can be expressed as (4).

$$P_w^D(T_{ij}^w, L_w) = \begin{cases} \min\left(1,\ 0.1T_{ij}^w\right), & w = r; \\ 0, & w = g, 0 < T_{ij}^w \le 20; \\ \min\left(1, 0.1(T_{ij}^w - 20)\right), & w = g, T_{ij}^w > 20; \end{cases} \tag{4}$$

4. Model

4.1. Problem description

The impact of aftershocks, mudslides, and other secondary disasters, not only leads to medical points failure but also causes road damage or interruption, in the early stage of post-earthquake relief. There is a mixed failure of facility nodes and routes in the emergency logistics network. The transport network diagram with the point-edge mixed failures in the early stage of post-earthquake relief is shown in Figure 2. As can be seen from Figure 2, based on the failures of facility points H and G, the secondary disaster also leads to the interruption of roads between affected point 4 and medical point D, and between affected point 4 and medical point E. At this time, ambulances cannot normally pass on the two roads, so it is necessary to use helicopters to transport the wounded to ensure timely treatment, reduce the death rate of the wounded, and improve the efficiency of emergency rescue.

The purpose of emergency rescue is to treat as many casualties as possible in the shortest time and reduce the death rate of the wounded. Therefore, the goal of the model is to minimize the expected death probability of casualties.

4.2. Assumptions

Model assumptions are as follows. First, the location of affected points and medical points is known, and the resources available at the medical point are limited. Second, each medical point can serve multiple casualty groups at the same time, and each casualty group can be assigned just one medical point. Third, the casualty groups have been classified in advance according to the trauma index of the injured. The severe injuries should be treated first according to the medical resources and ambulance and helicopter transport conditions. Four, each ambulance can only transport two casualties at a time, and each helicopter can transport four casualties at a time.

4.3. Notations

The parameters are as follows.

I: Set of affected points, $i \in I$;
J: Set of medical points, $j \in J$;
S: Set of Scenarios, $s \in S$;
R:The severe state of casualties (marked as red);
G:The minor injury state of casualties (marked as green);
W:Set of injury states, ;
P_w^D:The death probability of casualties;
H: Set of ambulances, $h \in H$;
N: Set of rescue helicopters, $n \in N$;
M: A large positive integer number;

d_{ij}: Transportation distance from affected point i to medical point j;

ε_{ij}: Degree of route damage between affected point i and medical point j; if $\varepsilon_{ij} > 0.5$, the route is disrupted, and the ambulances cannot pass. Then, the helicopter transportation should be considered. With the support of modern remote sensing technology and communication technology, the damage degree of route in the early stage after earthquake can be sensed in real time without constant trial and error.

d'_{ij}: Generalized transportation distance from affected point i to medical point j. The more damaged the route, the slower the vehicle speed, and the longer the transport time. That is, the longer the d'_{ij}. d'_{ij} can be obtained according to the method mentioned in literature (50), as $d'_{ij} = \begin{cases} d_{ij}\left(1+\varepsilon_{ij}\right) & \varepsilon_{ij} \le 0.5 \\ M & \varepsilon_{ij} > 0.5 \end{cases}$.

t_{ij}: The time taken to transport the wounded from affected point i to medical point j;

T: The horizon of scheduling time,$\forall t \in T$;

$\triangle\ T_{ij}^w$: The waiting time for ambulances or helicopters rescue for a casualty with injury state w;

v_h: The speed of ambulance h;

v_n: The speed of helicopter n;

Q_j: The number of available resources at medical point j;

Q_h: The number of available ambulance h at medical points;

Q_n: The number of available helicopter n at medical points;

q_h: The number of casualties can be transported by ambulance h at one time;

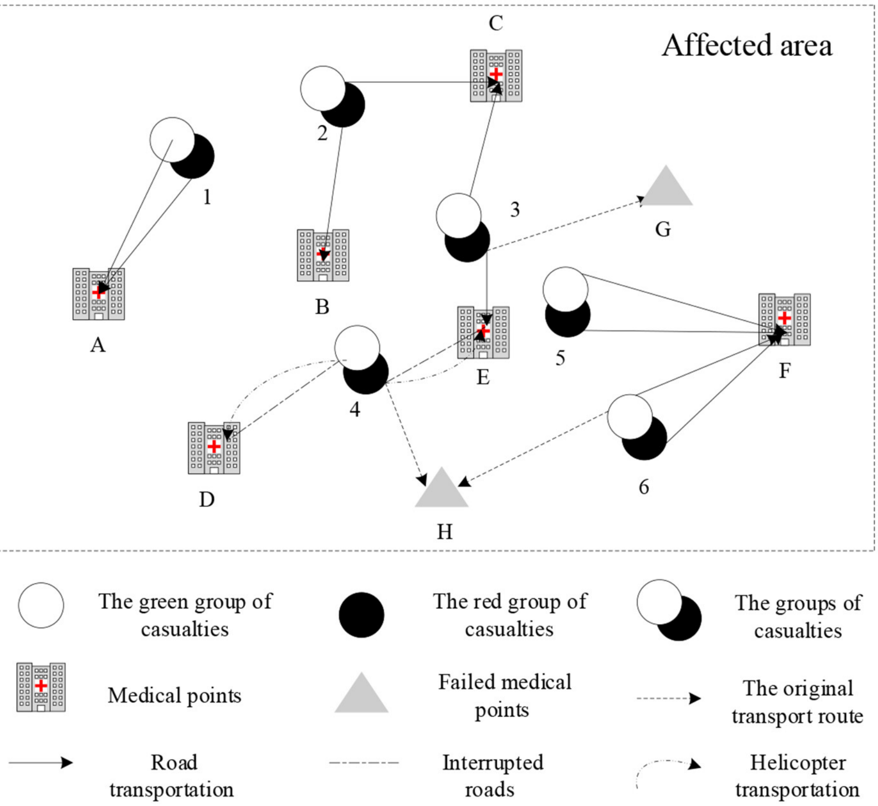

FIGURE 2
Transport network diagram in the early stage of post-earthquake relief.

q_n: The number of casualties can be transported by helicopter n at one time;

C_w: Resources needed to treat a casualty with injury state w, $W = \{w|w = r, g\}$;

a: Number of times an ambulance or a helicopter arrived at an affected point;

f_{iw}: The number of casualties with injury state w in affected point i;

β_{js}: $\beta_{js} = 0$represents the medical point j fail in scenario s; otherwise $\beta_{js} = 1$.

The decision variables are as follows.

k_{ijw}: The number of casualties with injury state w transported from affected point i to medical point j;

X_{ij}: A binary variable. If medical point j allocated to affected point i, $X_{ij} = 1$;otherwise $X_{ij} = 0$;

$X_{i'j}$: A binary variable. If medical point j reallocated to affected point i' after the initial allocated medical point j' failed, $X_{i'j} = 1$;otherwise $X_{i'j} = 0$;

$Y_{i'jh}$: A binary variable. If ambulance h travels from affected point i' to medical point j after the initial allocated medical point j' failed, $Y_{i'jh} = 1$; otherwise $Y_{i'jh} = 0$;

$Y_{i'jh}$: A binary variable. If ambulance h travels from affected point i' to medical point j after the initial allocated medical point j' failed, $Y_{ijh} = 1$; otherwise $Y_{ijh} = 0$;

Z_{ijn}: A binary variable. If helicopter n travels from affected point i to medical point j, $Z_{ijn} = 1$; otherwise $Z_{ijn} = 0$;

$Z_{i'jn}$: A binary variable. If helicopter n travels from affected point i' to medical point j after the initial allocated medical point j' failed, $Z_{i'jn}$=1; otherwise $Z_{i'jn} = 0$.

4.4. Mathematical formulation

The mathematical model can be formulated as follows.

$$Z = \min \sum_{w\in W} f_{iw} P_w^D, \quad \forall i \in I, j \in J \tag{5}$$

$$\sum_{w\in W} P_w^D = \begin{cases} \sum_{w\in W} \min\left(1,\ 0.1 \triangle T_{ij}^w\right), & w = r \\ 0, \quad w = g, 0 < \triangle T_{ij}^w \leq 20; & \forall i \in I, j \in J \\ \sum_{w\in W} \min\left(1,\ 0.1(\triangle T_{ij}^w - 20)\right), & w = g,\ \triangle T_{ij}^w > 20 \end{cases} \tag{6}$$

$$\sum Q_j \geq \sum_{h\in H} \sum_{w\in W} C_w k_{ijw}, \quad \forall i \in I, j \in J, s \in S \tag{7}$$

$$Q_j^0 = Q_j, \quad \forall j \in J \tag{8}$$

$$Q_j^t = Q_j^{t-1} - \sum_{w\in W} C_w {k_{ijw}}^{t-t_{ij}-1}, \quad \forall i \in I,\ j \in J,\ t \in T \tag{9}$$

$$\sum_{h\in H} aQ_h q_h \geq \sum_{h\in H} \sum_{w\in W} k_{ijw} Y_{ijh} + \sum_{h\in H} \sum_{w\in W} k_{i'jw} Y_{i'jh}, \ \forall i, i' \in I, j \in J \tag{10}$$

$$\sum_{n\in N} aQ_n q_n \geq \sum_{n\in N} \sum_{w\in W} k_{ijw} Y_{ijn} + \sum_{n\in N} \sum_{w\in W} k_{i'jw} Y_{i'jn}, \ \forall i, i' \in I, j \in J \tag{11}$$

$$\Delta T_{ij}^{r} = \begin{cases} (2a-1)t_{ij}, & Q_j^t - k_{ijr}C_r - k_{ijg}C_g \geq C_r, \quad \forall i \in I, j \in J, t \in T \\ M, & Q_j^t - k_{ijr}C_r - k_{ijg}C_g \geq C_r \end{cases} \quad (12)$$

$$\Delta T_{ij}^{r} = \begin{cases} (2a-1)t_{ij}, & Q_j^t - k_{ijr}C_r - k_{ijg}C_g \geq C_g, \quad \forall i \in I, j \in J, t \in T \\ M, & Q_j^t - k_{ijr}C_r - k_{ijg}C_g \geq C_g \end{cases} \quad (13)$$

$$t_{ij} = \begin{cases} d_{ij}(1+\varepsilon_{ij}) & \varepsilon_{ij} \leq 0.5 \quad \forall i \in I, j \in J \\ M & \varepsilon_{ij} \leq 0.5 \end{cases} \quad (14)$$

$$t_{ij} = \begin{cases} \frac{d'_{ij}}{v_h} X_{ij}\beta_{js} + \frac{d'_{i'j}}{v_h} X_{i'j} & \varepsilon_{ij} \leq 0.5 \\ \frac{d_{ij}}{v_n} X_{ij}\beta_{js} + \frac{d_{i'j}}{v_n} X_{i'j} & \varepsilon_{ij} > 0.5 \end{cases}, \quad \forall i, i' \in I, j \in J, s \in S \quad (15)$$

$$X_{i'j} = \begin{cases} 1, \left\{ j \middle| \bigcap (\min_{j \in Jj'} t_{i'j}, \beta_{js} = 1, \beta_{j's} = 0) \right\}, \\ 0, \quad otherwise \end{cases} \forall i, i' \in I, j \in J, s \in S \quad (16)$$

$$X_{ij}, X_{i'j}, Y_{ijh}, Y_{i'jh}, Z_{ijn}, Z_{i'jn} \in \{0, 1\}, \quad \forall i, i' \in I, j \in J \quad (17)$$

The objective function (5) is to minimize the total expected death probability of casualties. Constraint (6) denotes the death probability of casualties with different injury states. Constraint (7) is the resource limitation of medical points. Constraint (8) denotes the initial resources of medical points. Constraint (9) denotes the restriction of available resources at medical points at time t. Constraints (10) and (11) denote the restrictions on the number of available ambulances and helicopters from affected points to medical points respectively. Constraints (12) and (13) denote the waiting time for casualties with injury state g and r, respectively. Constraint (14) denotes the transportation distances from affected points to medical points. Constraint (15) denotes the time taken to transport casualties from affected points to medical points. Constraint (16) denotes each affected point will be served by the nearest open backup medical point if its initial allocated medical point has failed. Constraint (17) is a 0–1 variables restriction.

4.5. A robust optimization model

As the destructive earthquake occurred suddenly, and aftershocks may result in injuries in the initial stage after an earthquake, the number of casualties in affected points cannot be accurately estimated. Therefore, robust optimization was used to deal with the number of casualties to reduce the risk caused by uncertainty.

The parameter Γ_{iw} and corresponding variables are introduced to process the objective function and constraint Referring (51). Objective function equation (5) has uncertain variables of f_{iw}. Define the value range of $\tilde{f}_{iw}$ as $\left[f_{iw} - \hat{f}_{iw}, f_{iw} + \hat{f}_{iw}\right]$. f_{iw} is the nominal value of uncertain number of casualties. $\hat{f}_{iw}$is the maximum deviation of the uncertain number of casualties. We introduce variable f to transform the objective function (5) referring to (52). The objective function (5) is equivalent to (18)–(19).

$$\min f \quad (18)$$

$$\sum_{w \in W} \tilde{f}_{iw} P_w^D \leq f \quad (19)$$

A protection function for the number of casualties is introduced here as equation (20). Γ_{iw} is the control coefficient of the number of casualties.

A protection function for the number of casualties is introduced here as equation (20). Γ_{iw} is the control coefficient of the number of casualties. $\Gamma_{iw} \in [0, |J_{iw}|]$. Where J_{iw} is the number of Γ_{iw}. The objective of this robust method is that the number of casualties varies within their interval at most $\lfloor \Gamma_{iw} \rfloor$ affected points. Γ_{iw} is the balance between robustness and optimality. The bigger the Γ_{iw}, the more conservative the mode. The protection function for the number of casualties is introduced as with $\varphi(X, \Gamma_{iw})$ consideration of the uncertainty of the number of casualties. The objective function (5) can be transformed into formula (20).

$$\varphi(X, \Gamma_{iw}) = \max_{\{S_{iw} \bigcup \{t_{iw}\} | S_{iw} \subseteq J_{iw}, |S_{iw}| = \lfloor \Gamma_{iw} \rfloor, t_{iw} \in J_{iw} \backslash S_{iw}\}} \left\{ \sum_{i, w \in S_{iw}} \hat{f}_{iw} P_w^D + (\Gamma_{iw} - \lfloor \Gamma_{iw} \rfloor) \hat{f}_{t_{iw}} P_w^D \right\} \quad (20)$$

Where, S_{iw} represents the group set of the maximum number of casualties deviating from the nominal value. When $\Gamma_{iw} = 0, \forall i, w$, the robust model is equivalent to the nominal model.

Formula (20) can be expressed as (21).

$$\sum_{w \in W} \left\{ f_{iw} P_w^D + \max_{\{S_{iw} \bigcup \{t_{iw}\} | S_{iw} \subseteq J_{iw}, |S_{iw}| = \lfloor \Gamma_{iw} \rfloor, t_{iw} \in J_{iw} \backslash S_{iw}\}} \left\{ \sum_{i, w \in S_{iw}} \hat{f}_{iw} P_w^D + (\Gamma_{iw} - \lfloor \Gamma_{iw} \rfloor) \hat{f}_{t_{iw}} P_w^D \right\} \right\} \leq f, \forall i \in I, j \in J \quad (21)$$

If $\Gamma_{iw}, \forall i, w$ is a integer,$\Gamma_{iw} = \lfloor \Gamma_{iw} \rfloor, \forall i, w$, then

$$\sum_{w \in W} \left\{ f_{iw} P_w^D + \max_{\{S_{iw} \bigcup \{t_{iw}\} | S_{iw} \subseteq J_{iw}, |S_{iw}| = \lfloor \Gamma_{iw} \rfloor, t_{iw} \in J_{iw} \backslash S_{iw}\}} \left\{ \sum_{i, w \in S_{iw}} \hat{f}_{iw} P_w^D \right\} \right\} \leq f, \forall i \in I, j \in J \quad (22)$$

If $\Gamma_{iw} = 0, \forall i, w$,all the number of casualties are nominal. When $\Gamma_{iw} = \gamma$, the number of casualties in all injury states deviates from the nominal values, the model is equivalent to the Soyster model. As Γ_{iw} changes, the conservatism of the model also changes accordingly. The objective function (5) can be finally transformed into the following expressions based on the strong duality.

$$\sum_{w \in W} f_{iw} P_w^D + \mathcal{Z}_{iw} \Gamma_{iw} + \sum_{i \in J_{iw}} \mathcal{P}_{iw} \leq f \quad (23)$$

$$s.t. \begin{cases} Z_{iw} + \mathcal{P}_{iw} \geq \hat{f}_{iw} P_w^D \\ \mathcal{P}_{iw} \geq 0, \\ Z_{iw} \geq 0, \\ \forall i, w \in S_{iw}, \forall w \in W \end{cases} \quad (24)$$

Therefore, the robust optimization model considering the uncertain number of casualties can be given as follows.

$$\min f \quad (25)$$
$$s.t.(6) - (17).$$

5. Algorithm

The built model is a 0–1 mixed integer non-linear programming model, which cannot be solved by exact algorithms such as branch and bound algorithm or operations research software such as CPLEX. An improved integer-coded PSO algorithm is designed to solve the model.

The algorithm steps are described as follows.

5.1. Population initialization

① Initialization of parameters: Set population size as *popsize*, maximum iterations as $\max gen$, learning factors as c_1 and c_2, inertia weight as w.

② Particle encoding and decoding: Supposing there are n casualty groups and k medical points in the model, each particle has a code length of n. Each position of the particle is a positive integer randomly generated between 1 and k, and denotes the relation of assign between a casualty group and a medical point. Taking Figure 3 for example, there are 6 medical points in the affected area, which are required to provide rescue services to 11 casualty groups. The length of the particle is 11. Casualty group 2 and 11 are assigned to medical point 1, casualty group 1 and 10 are assigned to medical point 2, and so on.

③ Initialization of the best value of individuals and groups: The initial location and velocity of particles can be randomly generated. The fitness value of the current population can be calculated by the fitness function. The fitness function is the objective function (25). The individual position is the optimal position of the current individual P_{best}. The minimum value of the current particle P_{best_value} is the initial optimal value of individuals that can be got by comparing the optimal values of all individuals. Then set the initial P_{best_value} as the best value of groups g_{best}.

5.2. Updating speeds and locations

Population speed and location can be updated as expressions (26) and (27).

$$v_{id} = w^* v_{id} + c_1 r_1 (p_{id} - x_{id}) + c_2 r_2 (p_{gd} - x_{id}) \quad (26)$$
$$x_{id} = x_{id} + v_{id} \quad (27)$$

In which, r_1,r_2 are uniform random numbers within the range of [0,1].

Traditional PSO is mainly used to solve the continuous optimization problem, while the model in this paper belongs to a discrete combinatorial problem. So, the updated particle positions and speeds need integer processing. Figure 4A is the result of an updating particle according to the particle update equations, and Figure 4B is the result of a particle rounds up to integers. Here, casualty group 5 and 10 are assigned to medical point 1, casualty group 1 and 8 are assigned to medical point 2, and so on.

5.3. Updating the best value of individuals

Comparing the current particle fitness value *fitness* with the individual historical optimal value P_{best_value}, the smallest value is taken as the current individual optimal value P_{best_value}, and its

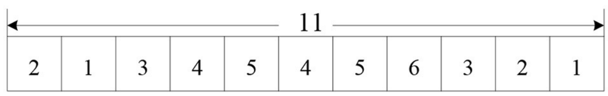

FIGURE 3
A diagram of particle coding.

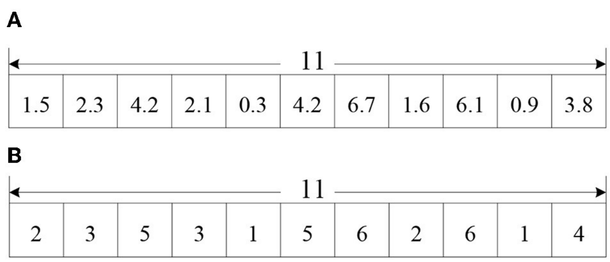

FIGURE 4
(A) Updated particle position. **(B)** Updated particle position round up to integers.

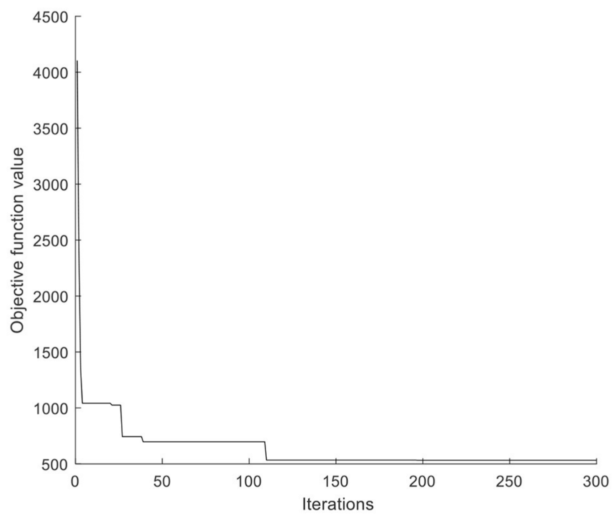

FIGURE 5
The convergence diagram of PSO.

corresponding position is taken as the current individual optimal position P_{best}.

5.4. Updating the best value of groups

Comparing the current individual optimal value P_{best_value} with the group historical optimal value g_{best_value}, the smallest value is taken as the current group optimal value g_{best_value}, and its corresponding position is taken as the current group global optimal position g_{best}.

5.5. Termination of the algorithm

Determining whether the algorithm reaches the maximum iteration, if so, the algorithm terminates and outputs the optimal solution. Otherwise, go to step 4.2 and continue the iteration.

6. Computational experiments

6.1. Case description and data

The data of emergency medical rescue for Ya'an, in the Lushan earthquake, Sichuan province of China is used for numerical simulation. Taking town or township as units, Lushan County has jurisdiction over 5 towns and 4 townships. So, 9 affected points are set in this article. The nominal number of casualties in each affected point is shown in Supplementary Table S1. The number of treatment resources required by casualties with injury state r and g is 3 units and 2 units respectively.

Data shows that the Chinese government and military deployed 15 helicopters to transport and rescue casualties in the Lushan earthquake. Therefore, the number of available helicopters in medical points is set as 15. According to the basic Standard for Medical Institutions (Trial) issued by the Chinese Ministry of Health, there is one ambulance for every 50,000 people in the city. The number of ambulances in Ya'an city and Chengdu city is about 30 and 300, respectively. In this paper, it is assumed that 50% of ambulances in Ya'an city can be used normally, and due to the time crunch, only 50% of ambulances from nearby Chengdu city are used for the transport of casualties. So, the total number of available ambulances in this paper is set as 165. The other parameters to the model are set as following. $C_r = 3$ units, $C_g = 2$ units, $v_h = 40$ km/h, $v_n = 120$ km/h, $q_h = 2$ persons, $q_n = 4$ persons, $T = 30$ h. The number of medical resource limitations for each medical point is shown in Supplementary Table S2. The distance between medical points and affected points is shown in Supplementary Table S3.

TABLE 4 Sensitivity analysis results of Γ_w.

Γ_w	Objective function value	Gap
0	561.553	0.00%
2	577.834	2.90%
4	595.820	6.10%
8	596.725	6.26%

TABLE 5 Comparison of the results solved by different algorithms.

Algorithm	Objective function value				CPU time (s)
	Min	Max	AVG	SD	
PSO	531.629	624.441	561.553	30.905	10.171
IA	855.691	965.369	898.150	35.622	12.762
GA	1,172.350	1,282.256	1,193.264	31.381	9.178
DE	1,123.614	1,272.032	1,194.355	56.335	8.886

TABLE 2 Treatment information at medical points.

Medical points	Casualty group with injury state r	k_{jr}	Casualty group with injury state g	k_{jg}	k_{jw}
1	R1, R2, R3	291	–	0	291
2	R6	178	G3	142	320
3	–	0	G2, G6	540	540
4	R4	116	G1	292	408
5	R7	42	G4, G5	324	366
6	R5, R8	126	G7, G8	222	348
7	R9	20	G9	40	60

TABLE 3 Comparison of the two schemes.

Schemes	Scenarios	Scenario 1	Scenario 2	Scenario 3	Scenario 4
1	Considering the point-edge mixed failures	531.629	531.629	531.629	531.629
2	Without considering the failures	459.334	751.217	851.767	612.256
–	Gap	−13.60%	41.30%	60.22%	15.17%

Referring to literature (46), four failure scenarios are set in Supplementary Table S4. The failure scenarios are set as follows. No medical point failure in scenario 1, medical point 2 failure in scenario 2, medical point 4 failure in scenario 3, medical point 7 failure in scenario 4. 0 means the medical point failure in Supplementary Table S4. Supplementary Table S5 shows the degree of route damage ε_{ij}.

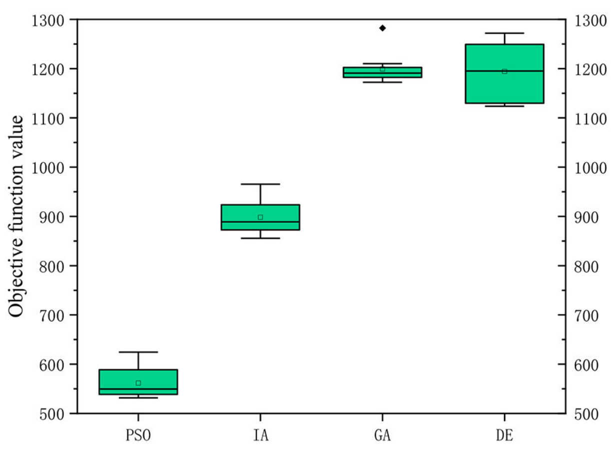

FIGURE 6
Computational accuracy comparison of the four algorithms.

6.2. Calculation results

The PSO parameters are set as follows. Population size $popsize = 100$, learning factors $c_1 = c_2 = 2$, inertia weight $w = 1$, the maximum iterations $\max gen = 300$. MATLAB R2018b is used for programming, and it runs on a notebook computer with Intel(R) Core (TM) I5-5200U CPU and 12G memory. The optimal solution of the results of 10 operations is taken as the final solution. The convergence time of the algorithm is 10.171 s, and the objective function is 531.629. The convergence diagram of the algorithm is shown in Figure 5. Table 2 and Supplementary Table S6 are treatment information at medical points and affected points respectively.

6.3. Considering failures vs. without considering failures

To test the reliability of the scheme got by considering the point-edge mixed failures, a comparison was made between two schemes. Scheme 1 is the current optimization results got by

TABLE 6 Scale analysis of the group 1.

Nodes	Algorithm	Objective function value			GAP	CPU time (s)
		Z^*	$Z-MAX$	$Z-AVG$		
10*10	PSO	518.290	724.181	628.742	–	13.886
	IA	775.670	1,010.727	881.677	33.18%	15.268
	GA	909.409	1,573.435	1,265.659	43.01%	10.267
	DE	910.378	1,167.492	1,000.632	37.17%	10.818
10*20	PSO	1,610.292	2,331.576	1,961.454	–	26.414
	IA	1,825.655	2,764.848	2,331.196	11.80%	26.985
	GA	2,348.573	3,265.085	2,852.104	28.39%	24.359
	DE	2,133.259	2,917.516	2,480.780	20.93%	23.422
10*30	PSO	2,882.112	3,589.796	3,319.307	–	38.898
	IA	2,900.485	3,706.958	3,392.738	0.63%	40.256
	GA	3,580.927	4,248.524	3,859.806	19.51%	39.245
	DE	3,539.897	4,017.549	3,790.272	12.43%	38.429
10*40	PSO	5,403.128	5897.38	5,605.815	–	51.517
	IA	5,621.404	7,186.703	6,506.498	3.88%	53.541
	GA	6,636.561	8,432.381	7,456.442	18.59%	53.149
	DE	6,432.144	7,571.784	7,043.505	20.41%	52.498
10*50	PSO	8,684.691	9,947.969	9,320.860	–	64.694
	IA	9,452.603	10,039.604	9,750.315	8.12%	70.845
	GA	8,952.025	11,020.991	10,021.034	2.99%	65.754
	DE	9,308.26	9,877.368	9,501.766	1.90%	64.691

Z, Objective function value; Z^*, the best objective function value; $Z-AVG$, the average value of Z; GAP, $[Z^*(\text{algorithm}) - Z^*(\text{PSO})]/Z^*(\text{algorithm})*100\%$.

TABLE 7 Scale analysis of the group 2.

Nodes	Algorithm	Objective function value			GAP	CPU time (s)
		Z^*	$Z - MAX$	$Z - AVG$		
15*20	PSO	650.165	856.959	753.769	–	34.923
	IA	839.106	1,044.125	972.196	22.52%	36.215
	GA	856.959	1,243.259	1,021.565	24.13%	35.512
	DE	856.497	1,191.873	1,029.144	26.76%	34.048
15*30	PSO	1,752.119	2,488.724	2,078.086	–	50.588
	IA	1,973.053	2,815.589	2,257.744	11.20%	54.154
	GA	2,118.788	3,032.033	2,487.702	17.31%	50.455
	DE	2,162.947	2,914.494	2,579.405	19.44%	49.081
15*40	PSO	3,108.708	3,754.086	3,346.931	–	65.382
	IA	3,032.033	4,257.05	3,524.326	−2.53%	71.452
	GA	3,251.877	4,433.367	3,949.915	4.40%	64.514
	DE	3,257.023	4,390.083	3,759.763	10.98%	64.017
15*50	PSO	5,543.338	6,340.27	5,981.089	–	78.216
	IA	5,758.349	6,878.194	6,165.836	3.73%	82.041
	GA	5,596.413	6,983.324	6,219.371	0.95%	81.463
	DE	5,436.843	6,799.166	6,103.492	2.01%	80.470
15*60	PSO	9,091.521	9,950.73	9,456.331	–	91.231
	IA	9,210.278	9,995.259	9,592.015	1.29%	97.778
	GA	9,698.788	11,177.334	10,534.336	6.26%	93.544
	DE	9,917.568	10,815.637	10,327.333	8.43%	92.102

considering the point-edge mixed failures. Scheme 2 is the results got without considering the failures. It is noted that the original objective function value in scheme 2 contains no factors of failures. The objective function value under each scenario in scheme 2 should be recalculated considering the facility failures and road disruption again (Table 3).

The results show that when there is no failure (scenario 1), the casualty scheduling results under scheme 1 are slightly worse than those under scheme 2. However, when the failure occurs after the earthquake, the solution result considering the failures is better than that without considering the failures. As shown in scenario 3, the total expected death probability of casualties under scheme 2 was 60.22% higher than scheme 1. Therefore, considering the point-edge mixed failure in advance can make more casualties receive timely treatment and reduce the death rate. The reliability of the system can be improved by considering the failures in the design stage of the emergency rescue network.

6.4. Robust optimization vs. deterministic optimization

To verify the effectiveness of the robust optimization model, the running results of the robust optimization model and the deterministic model were compared in the same scenario. Four numerical examples are designed according to different control coefficients Γ_w, and the maximum disturbance value of casualty number deviating from the nominal value is 20%, that is $\hat{f}_{iw} = 0.2 \times f_{iw}$. Table 4 shows the sensitivity analysis results of different robust control coefficients Γ_w. In general, although the objective function value of the robust optimization model is higher than that of the deterministic model, the gap is not significant. It shows that the robust optimization model can reduce uncertain risk. From the results of sensitivity analysis of Γ_w, the smaller the Γ_w, the stronger the robustness of the model. With the increase of the uncertainty of casualty numbers, the objective function value increases. The gap between the robust optimization model and the deterministic model (when Γ_w is 0) is gradually increasing. The appropriate scheme should be chosen according to the uncertain situation in practical decision-making.

6.5. Algorithm performance analysis

To test the performance of PSO, the algorithm was compared with GA, IA and DE. Each algorithm was run 10 times. The results are shown in Table 5 that the PSO is significantly superior to other algorithms. The average objective function value calculated by PSO reduces by 53.2% compared with GA, 37.5% compared with IA, and 53.0% compared with DE. The computational accuracy of PSO is better than GA, IA and DE, as shown in Figure 6.

TABLE 8 Scale analysis of the group 3.

Nodes	Algorithm	Objective function value			GAP	CPU time (s)
		Z^*	$Z-MAX$	$Z-AVG$		
20*20	PSO	632.999	936.483	759.6515	–	42.126
	IA	849.089	1,173.23	1,015.6294	25.20%	43.546
	GA	820.388	1,235.643	998.1089	23.89%	43.255
	DE	904.581	1,168.351	1,059.019	28.27%	42.459
20*30	PSO	1,506.62	1,798.516	1,648.0398	–	56.745
	IA	1,662.516	2,567.568	2,066.8692	20.26%	59.455
	GA	1,882.057	2,798.983	2,500.5531	34.09%	57.642
	DE	1,964.425	2,736.591	2,283.3327	27.82%	56.593
20*40	PSO	2,230.89	2,952.151	2,501.9441	–	73.941
	IA	2,569.914	3,290.935	2,950.2068	15.19%	78.366
	GA	2,609.005	3,149.086	2,885.3733	13.29%	72.031
	DE	2,582.686	3,054.551	2,837.5028	11.83%	72.603
20*50	PSO	4,602.979	5,212.538	4,964.0735	–	85.426
	IA	5,106.732	5,611.11	5,342.7636	7.09%	89.484
	GA	5,004.926	5,852.391	5,389.0979	7.89%	83.749
	DE	5,255.002	5,966.101	5,576.6224	10.98%	83.519
20*60	PSO	8,445.469	10,071.947	8,973.9028	–	98.203
	IA	9,201.623	10,543.646	9,928.9542	9.62%	105.628
	GA	8,616.743	10,223.87	9,201.7031	2.48%	99.946
	DE	8,816.551	10,913.478	9,851.5502	8.91%	98.023

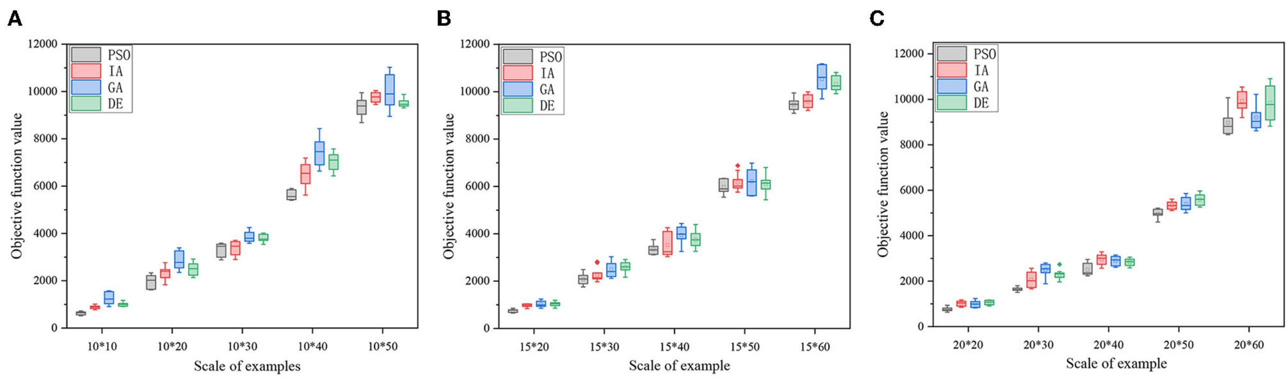

FIGURE 7
(A) Box diagram of group 1. **(B)** Box diagram of group 2. **(C)** Box diagram of group 3.

To further test the performance of the algorithm, three groups of examples are set for scale analysis. Each group contains five examples. The three groups have 10, 15 and 20 candidate medical points respectively. The calculation results are shown in Tables 6–8, and the box diagrams of the four algorithms for the three groups are shown in Figures 7A–C. The results show that PSO is better than GA, IA and DE obviously in terms of calculation accuracy. Among the 10 examples, only one example IA is better than PSO. The computational accuracy of PSO is better than GA, IA and DE for most examples. Therefore, the PSO designed in this paper can increase the optimization ability of the algorithm and has a good performance.

7. Conclusions

A robust optimization model was established in this paper to minimize the total expected death probability of casualties in the early stage of emergency rescue after an earthquake, considering the characteristics such as casualty classification, injury deterioration, point-edge mixed failures, medical resource limitation, and casualty number uncertainty. An improved PSO is proposed to solve the problem. Numerical experiments are conducted to verify the effectiveness of the model and algorithm under the context of the Lushan earthquake in China.

The results reveal that the operation effect of the emergency rescue network is significantly improved, and the optimization results are more reliable if the failure scenario is considered in advance. Moreover, robust optimization considering the casualty uncertainty can reduce the uncertainty risk of the system. Therefore, it is necessary to consider the point-edge mixed failures and casualty uncertainty simultaneously in the design stage of the emergency rescue network to establish a more reliable emergency rescue network.

Future research can consider the characteristics of the later stage of post-earthquake rescue comprehensively to study the casualty scheduling problem in the post-earthquake emergency recovery period while considering factors such as resuming normal passage of affected points and transporting the injured.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

YZ: writing and funding acquisition. YG: modeling and methodology. XH: data, algorithm, and computation. All authors contributed to the article and approved the submitted version.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpubh.2023.995829/full#supplementary-material

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Allocation of emergency medical resources for epidemic diseases considering the heterogeneity of epidemic areas

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Background: The resources available to fight an epidemic are typically limited, and the time and effort required to control it grow as the start date of the containment effort are delayed. When the population is afflicted in various regions, scheduling a fair and acceptable distribution of limited available resources stored in multiple emergency resource centers to each epidemic area has become a serious problem that requires immediate resolution.

Methods: This study presents an emergency medical logistics model for rapid response to public health emergencies. The proposed methodology consists of two recursive mechanisms: (1) time-varying forecasting of medical resources and (2) emergency medical resource allocation. Considering the epidemic's features and the heterogeneity of existing medical treatment capabilities in different epidemic areas, we provide the modified susceptible-exposed-infected-recovered (SEIR) model to predict the early stage emergency medical resource demand for epidemics. Then we define emergency indicators for each epidemic area based on this. By maximizing the weighted demand satisfaction rate and minimizing the total vehicle travel distance, we develop a bi-objective optimization model to determine the optimal medical resource allocation plan.

Results: Decision-makers should assign appropriate values to parameters at various stages of the emergency process based on the actual situation, to ensure that the results obtained are feasible and effective. It is necessary to set up an appropriate number of supply points in the epidemic emergency medical logistics supply to effectively reduce rescue costs and improve the level of emergency services.

Conclusions: Overall, this work provides managerial insights to improve decisions made on medical distribution as per demand forecasting for quick response to public health emergencies.

KEYWORDS

epidemic diseases, time-varying demand forecasting model, emergency medical resource distribution decision model, resource allocation, ε-constraint method, weighting sum method

1. Introduction

Since the turn of the twenty-first century, there have been numerous outbreaks of large-scale infectious diseases throughout the world. An epidemic occurs when an infectious disease spreads quickly and affects a significant number of individuals. Epidemic infections can spread widely in a short period, usually within 2 weeks or less (1). The most dangerous epidemics include SARS (2003), H1N1 influenza (2009), Middle East Respiratory Syndrome (2012), Ebola virus in West Africa (2014), Zika virus in Brazil (2015), and the continuing COVID-19, which broke out in late 2019 and rapidly became a pandemic, affecting the lives of millions at a global scale. With the emergence of the Novel Coronavirus variant, the number of new coronavirus cases in the world remains high every day. According to the latest real-time statistics from the WHO, as of 17:34 am Central European Time on December 1 (0:34 am Beijing time on December 2), the cumulative number of confirmed COVID-19 cases in the world has reached 63,957,2,819, with 6,615,258 cumulative deaths. These outbreaks pose a major threat to human physical and mental health, as well as to world economic progress.

Emergency medical logistics in response to public health emergencies is very important, but the research in this area is still inadequate (2). This work reviews the related literature by first focusing on prediction of the number of infected person infectious diseases and then discussing the approaches to logistics distribution for an emergency.

The use of the mathematical model to analyze the kinetic behavior of diseases dates back to Daniel Bernoulli's (3) 1760 research on the inoculation of smallpox infectious disease, which is known as the Bernoulli equation. Enko et al. (4) developed the discrete infectious disease model based on the binomial distribution for the first time by collecting the data on scarlet fever and measles and published the chain binomial model of scarlet fever and measles in 1889. The twentieth century saw the emergence of deterministic research on infectious illness models. Hamer (5) developed the dynamic measles model of herd immunity, which is a discrete state model with a bilinear infection rate. For the first time, a mass effect was proposed in the model, and it was assumed that the effective infection rate of individuals was proportional to the number of susceptible individuals. Ross (6) developed a differential equation model for the first time through the study of malaria transmission rules, demonstrating that malaria transmission could be controlled when the number of mosquitoes was reduced to a certain threshold and defined the standard infection rate and basic regeneration number. Kermack et al. (7) established a susceptible -infected-recovered (SIR) model after jointly studying the transmission trend of the Black Death in London, England, in 1665 and the plague in Mumbai, India, in 1906. Subsequently, the susceptible-infected-susceptible model was established in 1932 (8). Samsuzzoha et al. (9) established a susceptible-vaccinated-exposed-infected-recovered (SVEIRS) model, a diffuse zonal epidemic model of vaccination based on the SEIRS model, to investigate the impact of vaccination and transmission dynamics of influenza epidemics. Chinazzi et al. (10) predicted the influence of travel restrictions on the domestic and international transmission of an epidemic disease using a global congregational disease transmission model, and they find the quarantine in Wuhan slowed the overall progress of the epidemic in mainland China by 3–5 days and had a more significant impact on the international scale. Jumpen et al. (11–13) established a susceptible-exposed-infected-quarantined-recovered (SEIQR) model to simulate the evolution of the epidemic from the perspective of patient isolation, and used sensitivity analysis to investigate the impact of parameter uncertainty on the prediction of disease transmission. Yang et al. (14) updated the SEIR model to account for population flow and used deep learning methods to properly forecast the spread of an outbreak in China. Jia et al. (15) projected the relative frequency and geographical distribution of new coronavirus type 2 infection in mainland China before February 19, 2020, using the Wuhan population distribution. The publication of these scientific study findings established a highly effective theoretical and practical foundation for the efficient execution of epidemic prevention and control. Primarily, most scholars studied the laws of the epidemic disease transmission from two perspectives: the evolution of the outbreak population and the effect of related parameters on the development of the outbreak. They used the related mathematical theory and methods to prove the stability of the epidemic spread model, basic reproductive number, and threshold value for the existence of equilibrium of the model itself. These mathematical models can be used to describe the dynamic changes associated with various diseases and to forecast outbreak demand. In this paper, the system dynamics model is used to study the law of epidemic disease transmission.

For the dispatching and distribution of emergency supplies problem, scholars have established optimization models for allocating emergency materials in the event of a public health emergency, such as an outbreak of infectious diseases (16–26). Some of these scholars overlooked the impact of the evolution of infectious disease epidemics on supplies (16–21). Miniguano-Trujillo et al. (27) developed a multi-periodic integer programming optimization model and heuristic algorithm for allocating appropriate time to therapists for various patient types. A mixed-integer linear programming (MILP) model was established to achieve equity. Numerical results showed that treatment resources allocation based on population ratio is suboptimal. Implementing such a resource allocation policy may decrease the total number of infections and deaths, resulting in high costs that must be paid for equity. Repoussis et al. (28, 29) developed the optimal allocation of emergency medical resources in mass casualty events. Because it is critical to prioritize the allocation of emergency medical resources, the author turned the triage problem with limited resources into an ambulance route problem model to determine patients' evacuation sequence and destination hospital. To address the problem and find the optimal solution, an algorithm based on the column generation method was proposed. Pu (30) proposed a MILP model to tackle the allocation of patients to hospitals and treatment sequencing difficulties in mass casualty incidents, intending to effectively allocate limited resources in the response phase. Simultaneously, the model was built to minimize the total response time and flow time needed to treat all patients, and it was solved using precise and MILP-based heuristics. Ray (31) developed a model for emergency relief material transportation under various constraints to optimize transportation expenses. In general, current research results indicate that, within the context of public health emergency studies, emergency logistics management

FIGURE 1
Schematic diagram of state transition.

TABLE 1 Time-varying forecasting of medical resources mathematical notations.

Notation	Definition
S	Familiar and vulnerable susceptible people
E	Exposed people
I	Infectious people
H	Hospitalized infected people
R	Recovered people
J	A set of epidemic areas, j=1,2,3,..n;
$S_j(t)$	Numbers of common and vulnerable susceptible people in area j at the moment t
$E_j(t)$	Numbers of common and vulnerable exposed people in area j at the moment t
$I_j(t)$	Numbers of common and vulnerable infectious people in area j at the moment t
$H_j(t)$	Numbers of common and vulnerable hospitalized infected people in area j at the moment t
$R_j(t)$	Numbers of common and vulnerable recovered people in area j at the moment t
β_j^1	Exposure rate of susceptible people S in contact with infectious people I in area j
β_j^2	Exposure rate of susceptible people S in contact with exposed people E in area j
β_j^3	Exposure rate of susceptible people S in contact with asymptomatic infected people E in area j
σ_j^{-1}	Mean duration of latency (days)in area j
δ_j	The local medical treatment capacity mainly determines the rate at which infected people in areas j change to hospitalized patients
γ_j	Common and vulnerable recovery rate in area j

TABLE 2 Emergency medical resource distribution decision mathematical notations.

I	A set of supply points, i=1,2,3,.. m;
T	A set of time, one rescue cycle per day
X_j^t	The demand satisfaction rate of emergency medical resources in epidemic area j at the moment t
r_{ij}	Vehicle travel distance from supply point i to epidemic area j at the moment t
P_j^t	The stock of emergency medical resources that epidemic area j before moment t begins
$X_{j,min}^t$	The lower threshold of requirement satisfaction rate of emergency medical resources in epidemic area j at moment t,0< $X_{j,min}^t$ <1
Q_i^t	The stock of emergency medical resources at the supply point before moment t begins
ω_j^t	The degree of urgency in the demand for emergency medical resources in epidemic areas
K	The upper limit of the number of supply points for transporting medical resources to epidemic areas

is a significant research topic, and its study has profound theoretical and practical implications, demonstrating the necessity and importance of emergency logistics management. Additionally, it contributes significantly to the reduction of fatalities and property damage caused by emergencies. However, most studies (32, 33) focus on the one-time distribution of supplies and dispatch of emergency supplies, and rarely consider the emergency in epidemic areas, dynamic distribution of supplies, or actual situations in which different local medical treatment capabilities exist against the background of an epidemic and resulting in varying influences on the epidemic transmission evolution trend. After the outbreak of infectious diseases, the epidemic degree varies by epidemic location, and the demand for supplies in the epidemic area is determined by the number of confirmed infections.

The primary objective of this study is to quantify the actual situation in the epidemic area to distribute supplies, and help decision-maker to make best choices on the allocation of limited emergency medical resources to the appropriate places and quantities to halt the outbreak and mitigate its effects.

To be specific, this paper is based on human data collected in each of the affected areas. A particular point in time in the historical data is selected as the basis point. The personnel situation in each epidemic area at the decision time is forecasted based on the information at the basis point using the modified infectious disease model. The number of infected and hospitalized groups is simulated in each area to forecast patients' demand for emergency medical resources. Under the assumption that the demand for emergency medical resources for patients with infectious diseases and inpatients is known, we define emergency indicators for each epidemic area and develop a bi-objective optimization model to determine the optimal medical service allocation plan by maximizing the weighted demand satisfaction rate and minimizing the total vehicle travel distance.

In summary, this paper takes sudden infectious public events as the background, emphasizes emergency logistics schedule optimization, and presents an emergency rescue logistics model based on infectious diseases transmission mechanism. First, based on the transmission rules of infectious diseases combined with the local medical treatment capability, the modified susceptible-exposed-infected-recovered (SEIR) model are proposed to predict the material demand of each epidemic area during the entire emergency rescue stage. Second, a mixed-integer programming model for multi-stage and multi-cycle emergency rescue logistics scheduling in multi-epidemic areas is built with fairness (34) and timeliness in mind, and the route selection of rescue vehicles and allocation of medical resources are optimized. Finally, using the linear weighting and ε-constraint method, the MILP model of multi-objective emergency rescue logistics scheduling is transformed into a single-objective model, and LINGO software

TABLE 3 Coordinates and number of residents at resident demand node I.

NumberJ	1	2	3	4	5	6	7	8
S_0	8million	5million	3million	4million	2million	3.5million	2.5million	5.5million
E_0	5,000	4,000	2,000	3,000	1,000	3,000	2,000	5,000
I_0	600	500	300	400	200	400	300	600
H_0	180	125	120	100	20	60	60	125
R_0	156	95	126	75	22	23	36	110
β_j^1	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
β_j^2	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
β_j^3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
σ_j	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
δ_j	0.1	0.05	0.2	0.05	0.1	0.05	0.04	0.1
γ_j	0.2	0.15	0.3	0.15	0.1	0.1	0.1	0.15
α_j	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
P_j^2	193	105	89	108	92	85	57	172

TABLE 4 Vehicle travel distance from the supply point to the epidemic area.

r_{ij}	1	2	3	4	5	6	7	8
A	390	370	880	750	145	200	235	515
B	620	635	1,100	1,050	355	240	205	540
C	550	440	500	305	625	700	800	340
D	450	400	780	725	240	175	325	220

and YALMIP toolbox MATLAB program are used to validate the numerical examples.

2. Methods

2.1. Model assumptions

(1) The local population is relatively steady, regardless of migration, natural birth rate, or death rate.
(2) The infected individual requires pharmacological therapy following hospitalization.
(3) Individuals who have recovered get permanent immunity.
(4) It is assumed that the functional relationship between the demand for emergency medical resources and the number of infected individuals in the epidemic area is known.
(5) It is assumed that the demand for supplies in the epidemic area and reserves of relief centers can be forecasted, as well as the number of and geographic location of epidemic areas.
(6) This paper does not consider the number of vehicles, transportation mode, transportation capacity limits, or other related factors while implementing quarantine policies during an epidemic.

2.2. The time-varying demand forecasting model

According to the unique characteristics of the spread of infectious diseases, the precise allocation of emergency supplies during an epidemic can be summarized as follows: (1) During the early stages of an epidemic, it is necessary to quantify the extent of the emergency in epidemic areas. The epidemic locations are diverse, and each area has a unique crisis circumstance. (2) Because supplies demand are highly correlated with the number of confirmed infections, it is vital to forecast the demand in the epidemic area based on the number of infected people.

Based on the characteristics of the initial spread of infectious disease, hence the SEIHR warehouse models are created. We categorize the affected area's population into six subgroups: susceptible (S), exposed (E), infective (I) who have developed symptoms following the incubation period but have not been hospitalized or isolated, hospitalized infected (H), and recovered (R). $N = S + E + I + H + R$ is used to calculate the total population in each epidemic area. Figure 1 shows the transfer of this model between these epidemic classes. Table 1 shows the definitions of the time-varying forecasting of the medical resources model.

The susceptible population (S) reduce as a result of exposure to exposed, infected, and asymptomatic infected people, and they will enter the incubation period of exposure (moving to class E).As shown in formula 1.

The exposed population (E) become infected (moving to class I) with evident symptoms.As shown in formula 2.

The infected population (I) enter the inpatient stage (moving to class H) according to the local medical treatment capability. As shown in formula 3.

After treatment, the hospitalized population (H) reduces and enter the recovery population (moving to class R). As shown in formula 4.

The recovery population is immune to this disease.

2.3. SEIHR model

$$\frac{dS_j}{dt} = -\beta_j^1 S_j(t)I_j(t) - \beta_j^2 S_j(t)E_j(t) \quad (1)$$

$$\frac{dE_j}{dt} = \beta_j^1 S_j(t)I_j(t) + \beta_j^2 S_j(t)E_j(t) - \sigma_j E_j(t) \quad (2)$$

$$\frac{dI_j}{dt} = \sigma_j E_j(t) - \delta_j I_j(t) \quad (3)$$

$$\frac{dH_j}{dt} = \delta_j I_j(t) - \gamma_j H_j(t) \quad (4)$$

$$\frac{dR_j}{dt} = \gamma_j H_j(t) \quad (5)$$

2.4. Emergency medical resource distribution decision model

Mixed-integer linear programming (MILP) is used to develop a deterministic resource allocation model. Table 2 shows the definitions of the Emergency medical resource distribution decision model.

2.4.1. Notation

$$\omega_j^t = \frac{I_j(t) + H_j(t)}{\sum_{j\in J} (I_j(t) + H_j(t))} \quad (6)$$

2.4.2. Decision variables

Based on the descriptions and assumptions of the abovementioned models, the following multi-objective emergency relief supply distribution decision model can be established for each time cycle, to maximize the weighted sum of the demand satisfaction rates and minimize travel distance:

X_{ij}^t: The quantity of emergency medical resources allocated from supply point i to epidemic area j at the moment t

y_{ij}^t: 0–1 variable: if emergency medical resources are delivered from supply point i to epidemic area j at the moment t, it is 1; otherwise, it is 0.

2.4.3. Objective function

Objective 1: To maximize the weighted sum of demand satisfaction rates for each period.

$$\max Z_1 = \sum_{j\in J} \omega_j^t X_j^t \quad (7)$$

Objective 2: To minimize the sum of driving distances per period.

$$\min Z_2 = \sum_{i\in I} \sum_{j\in J} y_{ij}^t r_{ij} \quad (8)$$

2.4.4. Constraints

Subject to

$$X_j^t = \min\left\{\frac{P_j^t + \sum_{i\in I} X_{ij}^t}{D_j^t}, 1\right\} \forall j \in J, t \in T \quad (9)$$

$$X_{j,\min}^t \le X_j^t, \forall j \in J, t \in T \quad (10)$$

$$\sum_{j\in J} X_{ij}^t \le Q_i^t, \forall i \in I, t \in T \quad (11)$$

$$X_{ij}^t (1 - y_{ij}^t) = 0, \forall i \in I, j \in J, t \in T \quad (12)$$

$$\sum_{j\in J} X_{ij}^t \le \max\left\{D_j^t - P_j^t, 0\right\}, \forall j \in J, t \in T \quad (13)$$

$$\sum_{i\in I} y_{ij}^t \le K, \forall i \in I, t \in T \quad (14)$$

$$y_{ij}^t \in \{0, 1\}, \forall i \in I, j \in J, t \in T \quad (15)$$

$$X_{ij}^t \ge 0, \forall i \in I, j \in J, t \in T \quad (16)$$

Constraint (9) is the formula for calculating the demand satisfaction rate. When the supply exceeds the demand, the demand satisfaction rate should be equal to one.

Constraint (10) establishes a minimal demand satisfaction rate for all epidemic areas, which reflects the fairness principle.

According to constraint (11), the quantity of emergency medical resources delivered from the central distribution center shall not exceed its stock.

Constraint (12) indicates the relationship between these two variables, that is, only when the quantity of goods X_{ij}^t dispatched from the supply point to the epidemic area is not equal to 0, then the y_{ij}^t is equal to 1.

The purpose of constraint (13) is to prevent the supply point from receiving more materials than required.

Constraint (14) demonstrates that one epidemic area can only be served by K supply point to prevent wasting of transport capacity.

Constraints (15) and (16) are constraints on variable values.

2.5. Model solution

The key to solving multi-objective (35–38) problems is to convert the multi-objective function into a single-objective programming problem using the weighted method, constraint method, and mixed-method, which is solved using the traditional single-objective programming method. The ε-constraint method is an exact approach that is capable of generating non-extreme efficient solutions. An ε-constraint method also performs well in mixed-integer multi-objective problems.

In this paper, the multi-objective problem is standardized using min-max first, and then the maximization objective function is converted into the minimization objective.

$$\min Z_1' = -Z_1 = -\sum_{j\hat{I}J} \omega_j^t X_j^t \quad (17)$$

TABLE 5 Current information of the epidemic area.

Epidemic area	1	2	3	4	5	6	7	8
I_0	1,307	1,139	497	877	327	877	624	1,307
H_0	286	166	192	131	65	108	83	265
ω_j^2	0.19307	0.15816	0.08351	0.12217	0.04751	0.11938	0.08569	0.19052
D_j^2	1,593	1,305	689	1,008	392	985	707	1,572

2.5.1. ε-Constraint method

An ε-constraint method is a well-known approach used for solving multi-objective problems. This method is to convert a multi-objective problem into a single-objective problem, where only one objective is optimized and the remaining objectives are treated as constraints. The general form of this algorithm is defined by Eq. (18), where X denotes the feasible set of the mathematical model:

$$\begin{aligned} &\min f_1 x \\ &\text{subject to } x \in X \\ &f_2 x \leq \varepsilon_2 \\ &\ldots\ldots \\ &f_n x \leq \varepsilon_n \end{aligned} \tag{18}$$

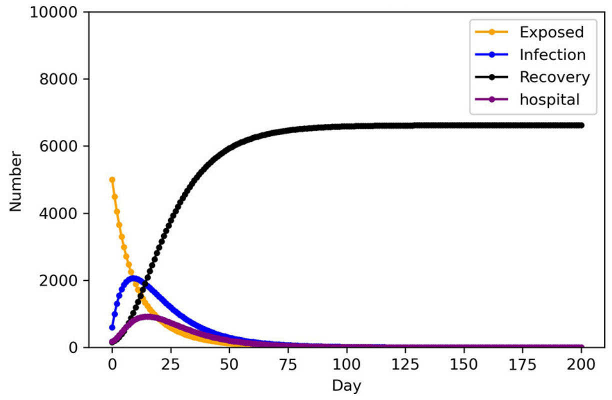

FIGURE 2
Epidemic trend in scenario 1 (Asymptomatic not included) of epidemic area 1.

2.5.2. Weighting sum method

Weighted sum method is the most frequently used technique to evaluate efficient solutions for a deterministic multi-objective optimization problem. The multi-objective problem is converted into a single-objective problem using the linear weighted grouping method, and assigning a weight to each sub-objective based on its importance. The overall objective function is:

$$\min Z = \lambda_1 \left(\frac{-\sum_{j\in J} \omega_j^t X_j^t - Z'_{1,\min}}{Z'_{1,\max} - Z'_{1,\min}} \right) + \lambda_2 \left(\frac{\sum_{i\in I}\sum_{j\in J} y_{ij}^t r_{ij} - Z_{2,\min}}{Z_{2,\max} - Z_{2,\min}} \right) \tag{19}$$

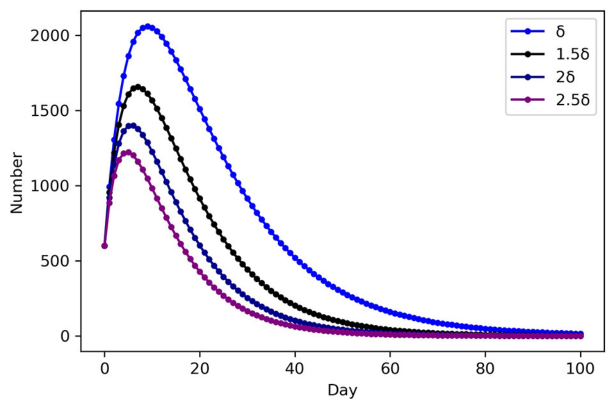

FIGURE 3
Epidemic trend in scenario 2 (Asymptomatic included) of epidemic area 1.

According to Formula (16), when the supply of emergency medical resources is sufficient to fulfill demand, the first term on the right end has a constant value of 1. In this case, the model is simplified as the optimization model to minimize the total driving distance. When the supply of medical resources for all points does not exceed the demand, the optimization model is reformulated into a MILP problem.

Constraint (9) is transformed into:

$$X_j^t = \frac{P_j^t + \sum_{i\in I} X_{ij}^t}{D_j^t} \leq 1, \forall j \in J, t \in T \tag{20}$$

2.6. Numerical experiments

2.6.1. Base case

Suppose that eight epidemic areas (numbered 1, 2, 3, 4, 5, 6, 7, 8) require immediate assistance as a result of the emergence of the epidemic. Four supply points (numbered A, B, C, and D) can provide emergency medical resources for the epidemic areas, with storage of A = 2,400, B = 2,500, C = 1000, and D = 1100, respectively. One supply point can only supply one epidemic area. Because the propagation of the epidemic differs from other

TABLE 6 Demand satisfaction rate of each epidemic area.

Epidemic area	1	2	3	4	5	6	7	8
Supply point	B	C	B	A	D	D	B	A
X_{ij}^{t}	1,400	1,000	591	900	225	875	509	1450
X_{j}^{t}	1	0.847	0.987	1	0.809	0.975	0.801	1

TABLE 7 Demand satisfaction rate of each epidemic area.

Epidemic area	1	2	3	4	5	6	7	8
Supply point	A	A	D	C	A	B	B	B
X_{ij}^{t}	1,085	1,090	600	900	225	714	650	1,136
X_{j}^{t}	0.802	0.916	1	1	0.809	0.811	1	0.800

TABLE 8 Impact of different minimum satisfaction rates on emergency rescue targets.

	1	2	3	4	5	6
$X_{j,\min}^{t}$	0.7	0.8	0.85	0.88	0.9	0.92
Total distance	4,045	4,045	4,045	4,815	4,815	3,285
Total satisfaction	0.94611	0.94611	0.94611	0.94605	0.94005	0.94001

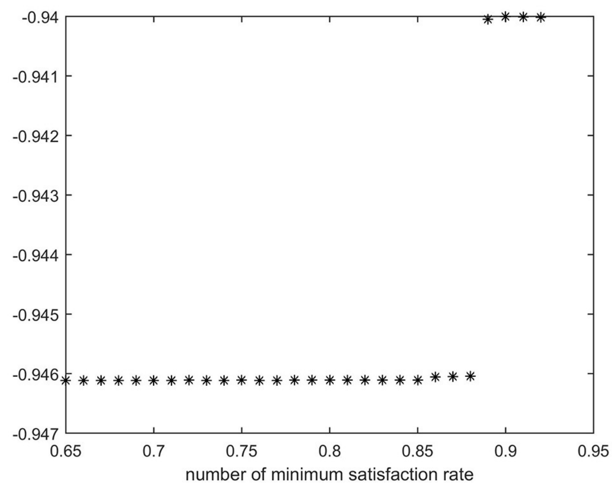

FIGURE 4
Impact of different minimum satisfaction rates on emergency rescue targets of the ε-constraint method.

TABLE 9 Impact of different minimum satisfaction rates on emergency rescue targets.

	1	2	3	4	5	6
$X_{j,\min}^{t}$	0.7	0.8	0.85	0.88	0.9	0.92
Total distance	2,375	2,975	3,285	3,285	3,285	3,285
Total satisfaction	0.8370	0.8793	0.9401	0.9400	0.9400	0.9400

situations and has an infectious time, it is difficult to determine the exact start date of the crisis. As a result, a date in the past is chosen as the start time. Different epidemic areas' start time information is shown in Table 3. Distances (in units/km) between the eight epidemic areas and the four supply points are shown in Table 4.

2.6.2. Experiments on the base case

The sensitivity analysis of the calculation results is conducted below, and the effect of adjusting the minimum demand satisfaction rates in the model is studied. When we change the number of supply points in an epidemic area, the results are also different.

3. Results

3.1. Base case

As indicated in Table 5, the SEIHR model is used to calculate the number of infected people, level of emergency, and total medical demand in each epidemic area after 2 days, Figure 2 show the variation in population numbers over time in epidemic area 1. Medical and health intervention is manifested by the level of medical treatment when infectious diseases occur, whether the medical resources are sufficient and complete, and whether all the patients can be collected when the number of infected patients increases rapidly, so that the patients can get timely and effective treatment. To improve the ability to treat patients can be regarded as the rate at which infected people in areas j change to hospitalized patients of infectious disease model. $\delta = (\delta, 1.5\delta, 2\delta, 2.5\delta)$, to analyze the impact on the number of infected people. Control variable method was adopted, remaining parameters remained unchanged, and SEIHR model was used to simulate the development of infected persons in Region 1, as shown in Figure 3.

The trend of the number of each population in the infectious disease model over time can be calculated, by using PYTHON programming to enter the parameters in Table 3 into the models. As illustrated in Figure 2, the number of infected and hospitalized patients grows over time and declines following adequate treatment, while the number of recovered patients increases throughout the whole stage. This result is consistent with the transmission mechanism of infectious diseases. From Figure 3, As medical and health care intervention gradually increases, δ of the corresponding model increases, the peak time of infection moved forward and the peak number of infected persons decreases accordingly. An adequate supply of medical resources is therefore critical to ending the outbreak quickly. In addition, early action on non-drug interventions are critical to epidemic control, and the lessons learned from epidemic control by WHO also show that early action will make significant progress in slowing and ultimately stopping outbreaks (39).

The model is programmed and the computation results are verified using the LINGO software and MATLAB YALMIP toolbox.

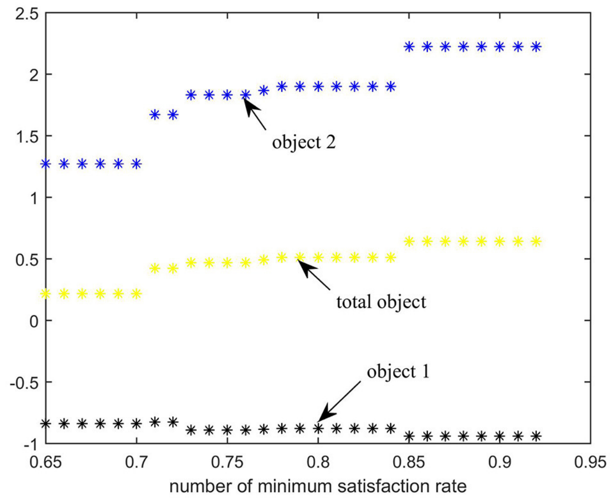

FIGURE 5
Impact of different minimum satisfaction rates on emergency rescue targets of the Weighting sum method.

TABLE 10 Satisfaction rate of each epidemic area and decision-making situation when $K = 2$.

Epidemic area	1	2	3	4	5	6	7	8
Supply point	A,B	A	B	D	B	B,D	B	C,D
X_{ij}^t	1,400	1,200	600	900	222	892	650	1,136
X_j^t	1	1	1	1	0.801	0.992	1	0.8

When fairness is the main objective, the results of the ε-constraint method are shown in in Table 6: $X_{j,\min}^t = 0.8$.

When the fairness and efficiency weights were 0.5, the results of the weighting sum method are shown in Table 7: $X_{j,\min}^t = 0.8$.

Generally speaking, the proposed dispatching and distribution model can satisfy the demand in each epidemic area to the greatest extent, meanwhile ensuring a fair allocation of materials among all the areas. Supplies will be delivered to each area from the nearest distribution center. Decision-makers can choose either objective based on their evaluations. The dual objective mixed-integer programming model, which takes into account both fairness and efficiency of the allocation of medical resources, also provides decision-makers flexibility to choose either objective based on their evaluations. Therefore, this work provides management insights for improving medical delivery decisions based on demand projections to rapidly respond to public health emergencies.

3.2. Experiments on the base case

3.2.1. Effect of the lowest satisfaction rate

This section primarily examines the effect of the difference in the minimum satisfaction rate of all epidemic areas on corresponding decisions, and the results of the ε-constraint method are presented in Table 8 and Figure 4.

The black dots in Figure 4 represent the value of objective function 1 at various levels of minimum satisfaction.

The results reveal that the value of the first objective function increases as the minimum satisfaction rate increases. Thus, the maximization of the weighted sum of the demand satisfaction rates shows a declining trend. This corresponds to the actual situation.

When the fairness and efficiency weights are 0.5, the results of the weighting sum method are shown in Table 9 and Figure 5.

The black dots (object 1), blue dots (object 2), and yellow dots (total object) represent the values of objective 1, the normalized objective 2, and the weighted value of the total objective at various minimum satisfaction rates, respectively.

As shown in Figure 5, when the fairness and efficiency weights are set to 0.5, the total weighted satisfaction rate and vehicle travel distance in the epidemic area increase with the increment of the minimum satisfaction rate.

The value of the minimum demand satisfaction rate is extremely important, and decision-makers should assign appropriate values to parameters at various stages of the emergency process based on the actual situation, to ensure that the results obtained are feasible and effective.

3.2.2. Effect of multiple supply points in an infected area

This section focuses on the influence of the different numbers of supply points on relevant decision-making in all epidemic areas where $X_{j,\min}^t = 0.8$. When K (The upper limit of the number of supply points for transporting medical resources to epidemic areas) $= 2$, the satisfaction rate of each epidemic area is shown in Table 10.

When $K = 2$, the weighted sum of the demand satisfaction rate is 0.9522, which is greater than when $K = 1$. When $K = 2$, the total travel distance is 4740 km, which is larger than the total travel distance of 4,045 km when $K = 1$. This trend is in line with common sense. Furthermore, when $K = 3$, the decision result is the same as when $K = 2$. Thus, even while the overall weighted satisfaction of residents in the epidemic area increases when supplies are delivered from two supply points, it happens that each supply point may deliver a small number of supplies, resulting in a waste of transportation resources. Therefore, for decision-makers, it is necessary to set up an appropriate number of supply points in the epidemic emergency medical logistics supply to effectively reduce rescue costs and improve the level of emergency services.

4. Conclusion

In comparison to traditional emergency logistics, emergency medical logistics (40) has three characteristics that raise the complexity and difficulty of solving logistical problems. To begin with, there is a dearth of demand-related information, such as the severity of the epidemic and the number of infected, as well as difficulties in marking distribution-related decisions. The incubation phase, in particular, results in a time delay in demand (41). Second, the disease can quickly spread from one location to another, resulting in a large-scale epidemic. Infection, recovery, and mortality rates typically vary across regions due to differences in individual physical conditions as well as habits, customs, and medical services provided by the hospitals in each region (42, 43). Third, unlike other forms of relief such as food, the substitutability of medical relief is imperfect. Specific medication cannot be completely replaced by another (44). This paper discusses how to allocate emergency supplies under two different infectious disease propagation scenarios. Specifically, this work contributes to the decision analysis of emergency medical logistics responses to public health emergencies in the following ways: First, based on the transmission rules of infectious diseases and local medical service capacity, we modify and develop a SEIHR (susceptible-exposed-infected-hospitalized-removed) model. These two models aim to forecast the time-varying demand for medical supplies in each epidemic area during the entire emergency rescue phase. Second, to find the optimal medical service allocation plan, we define emergency indicators for each epidemic area and propose a bi-objective optimization model to maximize the weighted demand satisfaction rate and minimize the total vehicle travel distance. Finally, we use linear weighting and the ε-constraint method to reformulate the bi-objective MILP model of emergency rescue logistics scheduling to a single-objective one. We also conduct numerical studies to examine the performance of the model.

4.1. Implications

Numerical results show that due to the hidden nature of asymptomatic infection, the number of infected people in infected areas will increase greatly. Decision-makers should assign appropriate values to parameters at various stages of the emergency process based on the actual situation, to ensure that the results obtained are feasible and effective. It is necessary to set up an appropriate number of supply points in the epidemic emergency medical logistics supply to effectively reduce rescue costs and improve the level of emergency services. Overall, this work provides managerial insights to improve decisions made on medical distribution as per demand forecasting for quick response to public health emergencies.

4.2. Limitations

Our study is hypothetical, without actual data. This study only evaluates how to predict the demand for medical aid resources and how to allocate resources based on the number of infected and hospitalized people in the epidemic areas. The supply points have also been fixed for the time being; however, these supply points can be adjusted continuously according to the number of supplies, location advantages, and the number of individuals serving in the epidemic area. Furthermore, the impact of population mobility and natural population growth rate on the spread of the epidemic is not considered in this work. Finally, the paper ignores the impact of material production capacity on decision-making.

In conclusion, the performance of emergency medical logistics may be improved significantly. Future research can take the material production supply chain, dynamic resource allocation based on locations of supplies, vehicle scheduling, and vehicle routing optimization problem into consideration. These factors help to establish a model that is more in line with the reality in medical resource allocation, thus more scientific and reasonable to solve practical problems.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

ZW: supervision. GJ: formal analysis, methodology, validation, and writing – original draft. XY, WC, and TY: visualization. QZ: writing – review and editing. BH: funding acquisition. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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The development of new remote technologies in disaster medicine education: A scoping review

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Background: Remote teaching and online learning have significantly changed the responsiveness and accessibility after the COVID-19 pandemic. Disaster medicine (DM) has recently gained prominence as a critical issue due to the high frequency of worldwide disasters, especially in 2021. The new artificial intelligence (AI)-enhanced technologies and concepts have recently progressed in DM education.

Objectives: The aim of this article is to familiarize the reader with the remote technologies that have been developed and used in DM education over the past 20 years.

Literature scoping reviews: Mobile edge computing (MEC), unmanned aerial vehicles (UAVs)/drones, deep learning (DL), and visual reality stimulation, e.g., head-mounted display (HMD), are selected as promising and inspiring designs in DM education.

Methods: We performed a comprehensive review of the literature on the remote technologies applied in DM pedagogy for medical, nursing, and social work, as well as other health discipline students, e.g., paramedics. Databases including PubMed (MEDLINE), ISI Web of Science (WOS), EBSCO (EBSCO Essentials), Embase (EMB), and Scopus were used. The sourced results were recorded in a Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flowchart and followed in accordance with the PRISMA extension Scoping Review checklist. We included peer-reviewed articles, Epubs (electronic publications such as databases), and proceedings written in English. VOSviewer for related keywords extracted from review articles presented as a tabular summary to demonstrate their occurrence and connections among these DM education articles from 2000 to 2022.

Results: A total of 1,080 research articles on remote technologies in DM were initially reviewed. After exclusion, 64 articles were included in our review. *Emergency remote teaching/learning education, remote learning, online learning/teaching, and blended learning* are the most frequently used keywords. As new remote technologies used in emergencies become more advanced, DM pedagogy is facing more complex problems.

Discussions: Artificial intelligence-enhanced remote technologies promote learning incentives for medical undergraduate students or graduate professionals, but the efficacy of learning quality remains uncertain. More blended AI-modulating pedagogies in DM education could be increasingly important in the future. More sophisticated evaluation and assessment are needed to implement carefully considered designs for effective DM education.

KEYWORDS

remote learning, remote technology, AI pedagogical approach, disaster medicine (DM), mobile edge computing (MEC), head-mounted display (HMD)

Introduction

The emerging evolution of remote technology in disasters has been developed in a multidisciplinary manner and has progressed tremendously in completely different settings, e.g., the COVID-19 pandemic and armed conflicts (1–4). The pandemic has changed the paradigm of traditional face-to-face classroom education and contributed to technology-driven pedagogies such as digital transformations and distance learning through hybrid telecommunications (5–7). The changes are not only affecting postsecondary student pedagogies in developed countries but also in developing countries such as the Southern African Customs Union (SACU) (8–10).

Over the last 20 years, the occurrence, impact magnitude, and economic loss from disasters have increased significantly and show an upward trend worldwide (11). According to the 2022 Disasters Year in Review (Emergency Event Database, EM-DAT), published by the Center for Research on the Epidemiology of Disasters (CRED), the category *natural hazards*, e.g., *flood, storm, and earthquake*, had dominated the *major events* of 2021, and the annual occurrence records are higher than those for the period covering 2001–2020. A total of 432 catastrophic events were recorded in 2021, which is significantly higher than the average of 357 annual catastrophic events for the 2001–2020 average. The catastrophic events of 2021 increased significantly compared to the previous two decades and resulted in extensive economic losses (Supplementary Data). In 2021, the *disastrous events* accounted for 10,492 deaths, 101.8 million people affected, and 252.1 billion USD in economic losses (12). Asia, especially China and India, remain the most severely impacted countries and has nearly half of the total number of mortalities and 66% of the total wounded. Northern America, especially the US, was severely affected by floods, storms, and the COVID-19 pandemic in 2021, which led to extensive economic losses of up to 112.5 billion USD. Furthermore, Europe was affected by unexpected cold and heat waves in 2021. The severe cold in France in April and wildfires in the Mediterranean regions (Algeria, Bulgaria, Cyprus, Greece, Italy, Macedonia, Tunisia, and Turkey) during the summer caused substantial agricultural damage with devastating consequences (13). The need for disaster medicine education to adequately prepare undergraduate students or graduate professionals for these kinds of disasters will require novel technologies, as well as traditional ones, to meet this challenge.

Due to the advent of artificial intelligence (AI) that relies on big data and the proliferation of the Internet of Things (IoT) for universal applications, e.g., smartphones, smart industries, and smart healthcare, wirelessly powered communication (WPC) devices and distant healthcare delivery systems are booming (14, 15). Mobile edge computing (MEC), a recently developed concept since 2014, is an emergent architecture where cloud computing services are extended to the edge of networks leveraging mobile base station (16). *Edge computing* refers to a broad set of techniques designed to move computing and storage out of the remote cloud (public or private) and closer to the source of data (17), i.e., the computing resources could be sent to the network's edge nearby the end-mobile devices (18). The MEC could not only efficiently perform emergency computational tasks but also provide advanced, realistic DM training. For example, unmanned aerial vehicles (UAVs) are deployed as flying IoT base stations (UAV-enabled sensors network) in order to enhance communication coverage and facilitate real-time data in the affected areas after disasters (19, 20). UAVs equipped with sensors have versatile uses from detecting toxic pollution to providing a 3-D realistic simulation to enabling an education scenario for first responders in disasters (21). Moreover, these UAVs equipped with miniaturized sensors could also support special missions such as sampling and identification of chemical, biological, radiological, and nuclear (CBRN) events for either civilian organizations or military forces (e.g., NATO Defense Alliance) (22). The significant technological development in mission-oriented UAVs could not only perform detection, identification, and monitoring of CBRN events in affected areas but could also be used as a useful tool for offering postgraduate courses in CBRN protection (22). Digital devices have transformed from "networked computers for collaborative learning" in the 1997–2006 period to "online digital learning" in

Abbreviations: COVID-19, coronavirus disease 2019; DM, disaster medicine; AI, artificial intelligence; MEC, mobile edge computing; UAVs, unmanned aerial vehicles; DL, deep learning; HMD, head-mounted display; EM-DAT, emergency event database; CRED, Center for Research on the Epidemiology of Disasters; IoT, Internet of Things; WPC, wirelessly powered communication; CBRN, chemical, biological, radiological, and nuclear; VR/AR/MR, virtual/augmented/mixed reality; XR, extended reality; GNSS, global navigation satellite system; CC, cloud computing; MCIs, mass casualty incidents; ML, machine learning; CNN, convolutional neural network; SVM, support-vector machine; ELITE-DR, E-learning in teaching emergency disaster response; DRR, Disaster risk reduction; FL, federated learning; FedTL, federated transfer learning; VRS, virtual reality simulation; SG, serious game; DRM, disaster risk management; InfoVis, information visualization; CQI, continuous quality improvement; Ue-WPIoT, UAV-enabled wireless powering IoT; WSNs, Wireless sensor networks; CS, crowd-sourcing; IoTEWS, IoT-based early warning system; IoE, Internet of Everything; IoNT, Internet of Nano Things; MOOCs, massive open online courses.

the 2007–2016 period (23, 24). By using a high-fidelity immersive head-mounted device (HMD) designed by virtual/augmented reality (VR/AR) or newly developed mixed reality (MR)/HoloLens technology, along with disaster risk big data, we can easily build more comprehensive scenarios and learning models for trainees while facing disasters (25). The AI-enhanced training platform is a feasible alternative for undergraduate medical students, professionals, or ordinary people to be familiar with pre-emergency preparedness, disaster assessment, or emergency response/evacuation in simulated settings rather than dangerous environments, e.g., fire, pandemic, earthquake, or toxic situations (26, 27). The HMD-based teaching tools were found to be more effective and viable than other digital devices in medical education (28). Extended reality (XR)-based HMD utilizes the concepts of AR, VR, and MR and could provide more beneficial effects on medical skills and knowledge in medical training (29).

Even though the immersive HMD could make it easier to come up with a new and interesting way for medical students to learn, the DM curriculum should be implemented using an evidence-based, multi-modal approach because training programs do not give students enough opportunities to do cooperative activities, group work, and social interaction at the same time (30). We will discuss HMD-based immersive VR (IVR) in DM education regarding new developments, training efficacies, and how participants value their experience with these technologies.

An extensive literature review was conducted in order to provide a cutting-edge evaluation of the development of medical school students' or health professionals' learning by using remote technologies in facing disasters or emergencies. This review checked different remote learning systems under development, the teaching effects of different applications, and the possible changes in the pedagogy of DM that could materialize in the future. This review focuses on the newly developed technologies applied in DM education and training programs for medical and other undergraduate students. The four specific queries are as follows:

1. What kinds of newly remote technologies have been developed in DM and DM education?
2. What are the related articles or keywords described in the field of DM education in recent years?
3. Could remote technologies adopted in learning pedagogies and training programs for medical staff improve their capabilities?
4. What future objectives will new DM learning attain or strive for?

Research methodology

Searching strategies and inclusion and exclusion criteria

Five major electronic databases, including PubMed database (MEDLINE), ISI Web of Science (WOS), EBSCO Essentials (EBSCO), EMBASE (EMB), and Scopus, from 1 January 2000 to 15 May 2022 were compiled in our review. All articles were from the Science Citation Index (SCI) and Social Science Citation Index (SSCI) databases. After the literature was reviewed, we obtained the related keywords with the high number of occurrences as queries with the following terms: *remote technology* (6, 31, 32); *remote learning* (6, 31, 33); *online learning or teaching* (7, 10); *emergency or disaster response* (34, 35); *disaster medicine education* (30, 36); *blended learning* (37–39); *mobile edge computing* (20, 40); *virtual or augmented reality* (23, 25, 41, 42); *drone* (14, 20, 43); *machine learning* (44, 45); *deep learning* (46, 47); and *federated learning* (48, 49). Similar articles included in references were also screened. The inclusion criteria were reports or peer-reviewed studies of education and training programs, which were focused on any kind of disaster or emergency such as medical, nursing, pharmacy, social work, or paramedical science, and also for other hospital staffs such as administrators; and peer-reviewed studies, accepted articles for publication, e.g., electronic publications (Epubs), and proceedings which were written in English. Two of our coauthors screened the abstracts for potential articles, and the full texts were checked in detail to decide whether they correlated with our eligibility criteria or not. The exclusion criteria were conference abstracts, unpublished manuscripts, and whitepapers available online; non-medical issues such as industrial or geoengineering planning or projects; articles not published in English; and articles on disaster medicine but do not mention specific education or training programs.

Data collection and bibliometric analysis

Information visualization (InfoVis) is a visual representation technique utilizing data from abstracts to allow researchers to quickly analyze and understand the huge amount of multidimensional data produced in emergencies (50). Bibliometrics is an InfoVis analysis that quantitatively and qualitatively evaluates citations to scientific publications by constructing and mapping citation graphs to a network representation (51–53). The VOSviewer is the most common tool specifically designed for constructing and visualizing research trends and the maps of co-occurrence keywords in health-related literature on natural disasters or epidemic outbreaks (54–56). The software generates network and cluster visualizations of the data, which can be useful in identifying patterns and relationships among the keywords, including the titles and abstracts of reviewed articles. Cluster Density Visualization is a vivid demonstration of the dataset, and the software will automatically be grouped in clusters according to those related keywords. High densities of connections among the keywords within a cluster will indicate that those keywords are highly related, while low densities of connections show that the keywords are less related. This representation provides a way to identify and explore the relationships between different groups of keywords. We used VOSviewer (v.1.6.18, 2022) to analyze the keywords from the semantic contents we retrieved from PubMed (reference). The keywords included "remote technology AND disaster education," "remote learning AND disaster medicine education," "remote learning experience AND disaster medicine education," "remote system AND disaster medicine education," "mobile edge computing AND disaster medicine education," "virtual /augmented reality AND disaster medicine education," "drone AND disaster medicine education," and "machine learning

AND disaster medicine education." VOSviewer maps the keywords according to the frequencies and the co-occurrences. According to the circle size which is proportional to the frequencies of the keywords, we chose the remote technology-relevant keywords.

Results

Searching process

The Preferred Reporting Items for Systematic Reviews Analysis and Meta-Analyses (PRISMA) charting and PRISMA extension for Scoping Reviews (PRISMA-ScR) statement were adopted in the flow of the literature search process (57, 58). In the first, 1080 relevant articles were screened from the databases: 402 from MEDLINE, 250 from WOS, 150 from EBSCO, 134 from EMB, and 144 from Scopus (Figure 1).

Duplicated publications from different databases were checked by two of our authors manually. After duplicates were removed, 450 articles were assessed for eligibility. A further 410 articles were excluded due to failure to correlate with our stated criteria. We added the extended articles, which have been highly cited by other websites (e.g., Google) but were not shown in our previous search of databases (i.e., 24 articles extended). All of the 64 articles in the online electronic databases that were published in peer-reviewed journals are considered to be reliable.

The changes in DM education (blended learning)

The "hybrid/blended learning" (technology-enhanced learning, problem-based learning, table-top exercise, and computerized simulations) (59, 60) core curriculum focusing on different kinds of disaster scenarios, either in-hospital (e.g., contaminated victims) or out-hospital events (e.g., landslides, floods, and earthquakes), has been implemented in a variety of DM applications and delivered to undergraduate medical or paramedic students in order to improve their disaster preparedness knowledge and the capabilities of prehospital disaster management (36, 37, 61).

The advent of remote technologies in DM education or training program

Many related state-of-the-art technologies have been integrated into disaster rescue, risk management, epidemic tackling, and remote learning and education (19, 31, 33, 43, 62–64). We reviewed three major categories of distance learning design in DM education and we discuss them in detail below.

Efficient MEC technologies for DM training and education

The emergence of computation-intensive applications such as MEC devices could provide wide spatial coverage in affected areas during disasters and could perform emergency computational tasks in civil and military areas, which significantly improve post-disaster management (18, 19, 65). The MEC technologies such as webcam/photo-realistic 3-D model imagery capture (66, 67), intelligent wearable medical equipment (point-of-care sonography) (68), robotics (69), and social media (70–72) have all been shown to be beneficial in a variety of emergencies.

For instance, flying UAVs/drones integrated with a MEC server (UAV-enabled MEC), in conjunction with the Global Navigation Satellite System (GNSS), real-time computer vision, and advanced photogrammetric techniques (including deep learning algorithms), could enable first responders to obtain accurate 3-D imagery of affected areas *via* cloud computing (CC) and aid in the rapid identification of victims (73, 74). Not only could drones be used in disaster mapping for search and rescue operations but also could provide an excellent resource for training paramedic students in mass casualty incidents (MCIs) (75). In addition, 80% of nursing students in the Emergency Nursing Master program at the Catholic University of Murcia (UCAM) reported a significant improvement in their self-perception and performance in the MCI simulation with the assistance of drones (76).

Machine learning applied in DM education

Machine learning (ML) algorithms, such as the evidence-based medicine (EBM) movement, have become a powerful prediction tool ranging from clinical diagnosis to enhancing desired healthy behaviors (77). The medical school curriculum as well as the postgraduate medical education within academic hospitals around the world are facing the challenges of this AI-driven data science revolution (78). Among them, deep learning (DL) was developed from traditional ML techniques and provides more accurate classifications and predictions in disasters, e.g., as victims' detection, image segmentation, and medical information processing, due to powerful computing capacity and the high availability of large datasets (79–81). For example, DL trains a system to filter the digital images and to aid in the prediction of whether a corresponding patient is infected with COVID-19 or not (82). In addition, using convolutional neural network (CNN) technology, a radiologist in a remote area may determine whether a patient's lung is impacted by COVID-19 using chest X-ray images (83, 84). CNN is the most established algorithm among various DL models, which is an artificial neural network dominant in computer vision tasks by stacking mathematical layer operations, i.e., convolution (83). Innovative digital technologies were found to boost AI detection performance during the COVID-19 pandemic while also enhancing learning models for medical professionals in disease diagnosis (46, 47, 85). DL could also detect and identify large amounts of data from social media messages (urgent and not urgent tweets) during a disaster and confirmed a high efficacy in detecting urgent tweets during hurricanes, based on a combined CNN, trained on average word embedding, and support-vector machine (SVM), trained on full word embedding (71). DL not only provides a modern computational platform and automated medical practice but also refers to a comprehensive human learning approach and has been integrated into medical education (86). E-learning in teaching emergency disaster response (ELITE-DR) among undergraduate medical students could provide

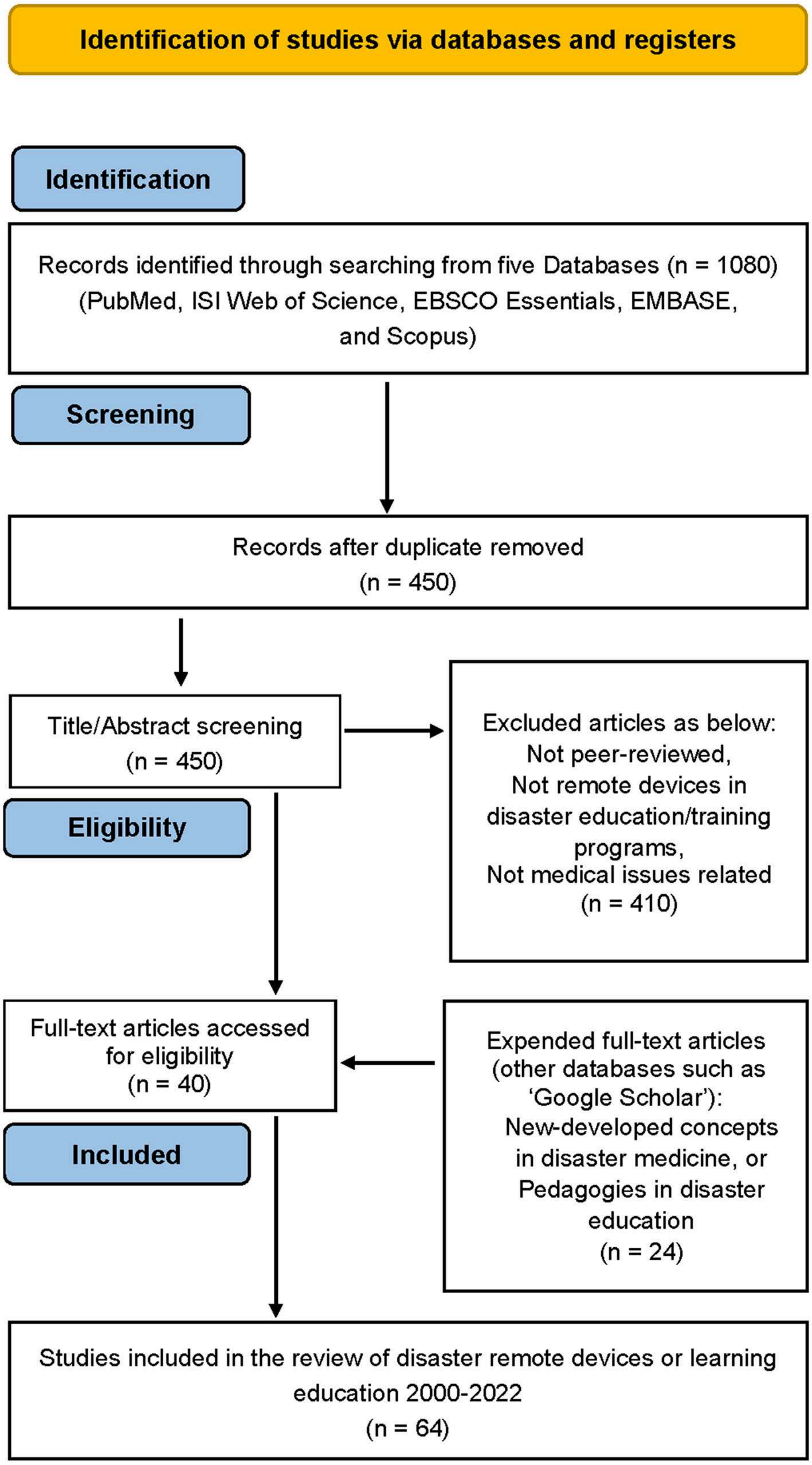

FIGURE 1
Flow of the literature search process (PRISMA chart)).

comprehensive levels of cognitive concepts and visual stimuli for disaster response medicine (87). However, surveys reveal few formal teaching programs incorporated into medical education about AI/ML, whether in Europe, the US, or even in Asian countries (88–91). For example, 66.5% of final year medical school students in Ireland reported zero hours of teaching on AI/ML during their degree, 43.4% had not heard of the term "machine learning," and 80.6% had not read any academic journal articles on AI/ML (44).

The applications of AI, ML, and DL have been widely introduced and developed for disaster management, i.e., in the aspects of hazard prediction, vulnerability assessment, disaster early warning systems, disaster monitoring, damage assessment, and post-disaster response (92). The preparedness for disaster risk reduction (DRR) (93) and the training on AI for disaster management (94) are important teaching models and could improve first responders' capability while facing different catastrophes. Federated Learning (FL) approach, a de-centralized data collection technique, generates more robust models without sharing data in a central server and enables collaborative training of multiple MECs (e.g., UAVs) locally (48, 95). FL trains at distributed MEC devices to offload data in order to reduce the data crowdsensing, delay transmission, and also protect IoT application privacy (96). FL could prove a more effective training model in disaster scenarios due to massive irrelevant data and a high flow of scalable IoT networks while in disasters. The privacy-preserved federated transfer learning (FedTL) approach could also provide and verify a real disaster image dataset collected from distributed social computing nodes (97). The new-developed FL model will give both AI and humans (e.g., first responders) a sophisticated training course and achieve better performance for the medical image learning model (98).

HMD-IVR devices applied in DM education

Virtual reality simulation (VRS) technology is widely used and it seems to be a viable training alternative in different disciplines, e.g., a simulation realistically of different hospital disaster scenarios, which could provide positive effects of confidence and necessary knowledge acquisition for healthcare professionals in hospital (99). Due to the features of reproducibility and repeatability of VRS, the newly developed technology could also improve CBRN training courses for both military and civilian responders to CBRN events (VERTIgO project) (100). VR delivers virtual scenarios and combines with multi-source data, 360 degrees video, and intuitive interaction interfaces to facilitate quality interprofessional education (101, 102). The so-called "Just-in-time" training programs could offer effective personal preparation and resiliency by enhancing responders' situational awareness in critical overloading situations, e.g., in the COVID-19 pandemic (103). Furthermore, the serious game (SG), one of the popularly used game genres nowadays, combines practical aspects with original amusement but is implemented for health or medical education (non-entertain) purposes (104). SG has been applied in improving medical technical skills such as laparoscopic surgery or arthroscopic intervention for postgraduate residency training in medical settings (105, 106). Disaster risk management (DRM)-related SG/simulation also provides a good educational and engagement tool for affected communities, policy-makers, and other vulnerable population (107). The SGs/simulations, with the realistically simulating disaster reality, offer assistance especially in the realm of disaster risk awareness raising, identifying hazards, undertaking preventive actions, empathy triggering, and perspective-taking (107). Moreover, 3-D video capture HMDs provide a more interesting way to interact and contribute to positive feedback responses from children, which are also vulnerable groups in disaster and public health emergencies (108, 109). Although the VRS technology shows a higher learning atmosphere, comprehensibility, and overall recommendation of teaching courses than those with a non-immersive screen (110), some articles showed conflicting results on VR HMD benefits or even no benefits at all (111, 112). Among them, technology limitations (surgical training), usability challenges (less powerful hardware), cybersickness, and limited participants' induced questionable assessment were potential limitations (113).

Bibliometric analysis for articles reviewed

By analyzing with VOSviewer, we obtained the co-occurrence MeSH keywords mapped as shown with Network and Cluster Density Visualization of the retrieved title and abstract (Figure 2). In the network visualization figure (Figure 2), the size of the circle is proportionate to the frequency of the keywords, and larger circles at keywords mean that they appear more frequently in the dataset. The keywords are categorized into six clusters according to the highly related connection. "COVID-19" classified in cluster 6, is correlated with the keywords "online learning," "online teaching," "remote learning," and "remote teaching" in cluster 1. The keyword "medical education" classified in cluster 4 also has the same correlation with the keywords "online learning," "online teaching," "remote learning," and "remote teaching" in cluster 1. The keywords were classified automatically into six clusters and are presented in Table 1.

Publication trends demonstrated by VOSviewer

Figure 3 presents the study trend as it varied from 2010 to the present. Early in 2020, the remote equipment applied to emergency management was studied. Then, the research target moved to telemedicine and remote sensing technology with the flourishing development of communication technology. While COVID-19 outbreaks had occurred by the end of 2019, the keywords "emergency remote teaching," "remote learning," "online learning," "emergency remote learning," "blended learning," and "emergency remote education" mirror the global education remote technology methods that were necessitated to educate the students and to keep safe social distances. Based on the correlation, it seems that people did a lot of studies related to education while they were isolated during the COVID-19 pandemic.

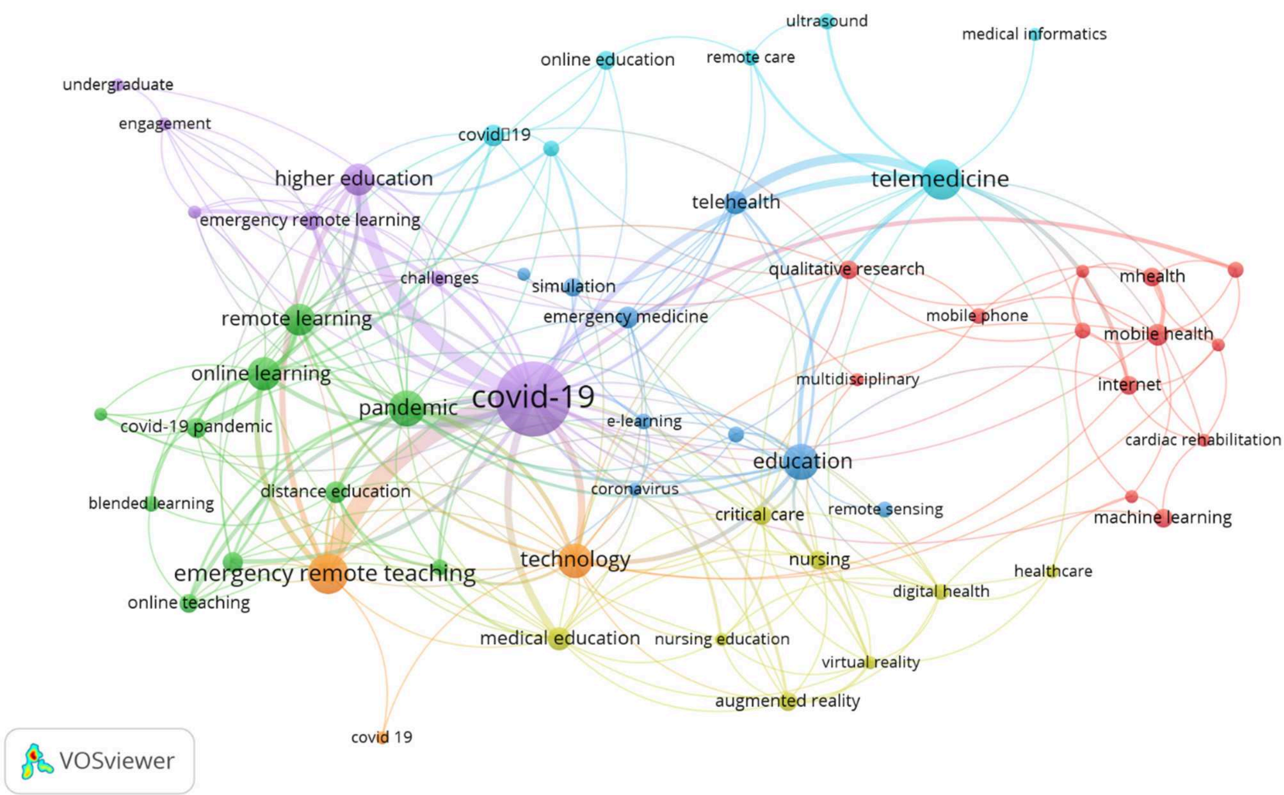

FIGURE 2
The network visualization figure of the screened keywords.

TABLE 1 Keywords classified as six clusters by VOSviewer.

Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
Blended learning	Artificial intelligence	Coronavirus	Augmented reality	Challenges	COVID-19
COVID-19	Cardiac rehabilitation	e-learning	Critical care	COVID-19	Emergency remote education
COVID-19 pandemic	e-health	Education	Digital health	Emergency remote learning	Medical informatics
Distance education	Internet	Emergency medicine	Healthcare	Engagement	Online education
Emergency remote teaching	Machine learning	Public health	Medical education	Higher education	Remote care
Online learning	Mental health	Remote sensing	Nursing	Pedagogy	Telemedicine
Online teaching	M-health	Simulation	Nursing education	Undergraduate	Ultrasound
Pandemic	Mobile applications	Telehealth	Virtual reality		
Remote learning	Mobile health	Tele-simulation			
Remote teaching	Mobile phone				
Teachers	Multidisciplinary				
Teaching	Qualitative research				
Technology	Smartphone				

Future education models proposed by AI-integrated platform

Figure 4 shows the current application technology and the future trend of DM education. Using UAVs and photography equipment to obtain real disaster scenes and recreating them using VRS technologies, such as VR, AR, and MR technologies can provide students with a more authentic learning experience. These technologies can be used to simulate real-world scenarios and provide a more immersive experience, which can help students better understand and prepare for potential disasters.

Big data analysis and advanced AI technologies, such as deep learning and federated learning, can also be used in disaster management education. For example, these technologies

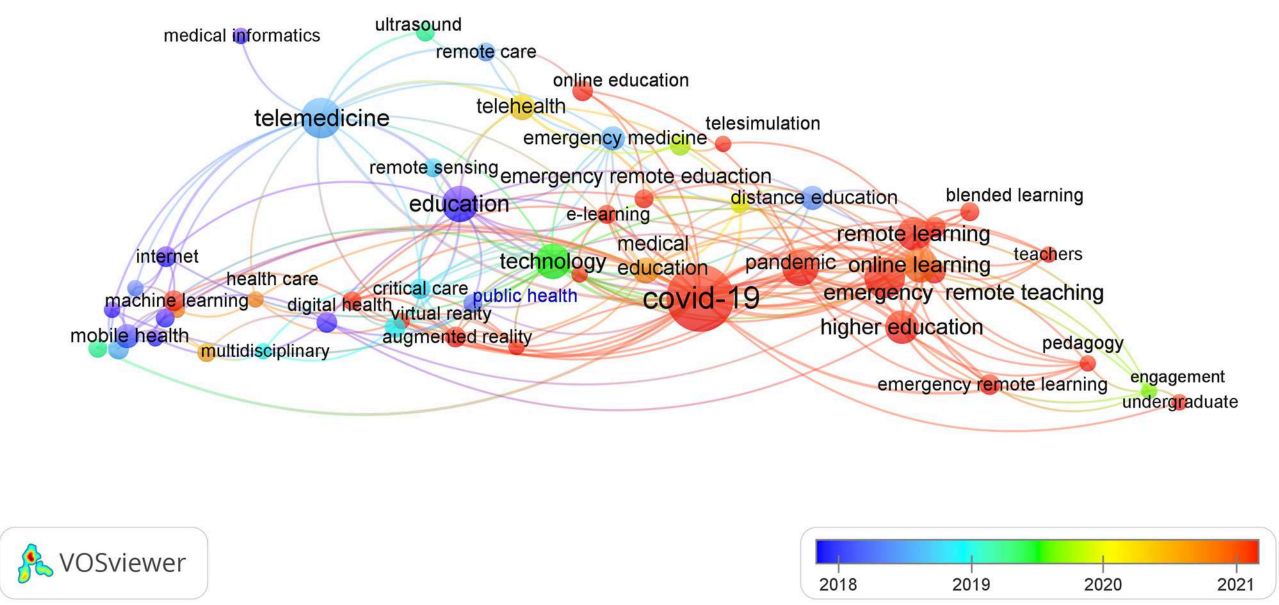

FIGURE 3
The variation of the screened keywords changed with time.

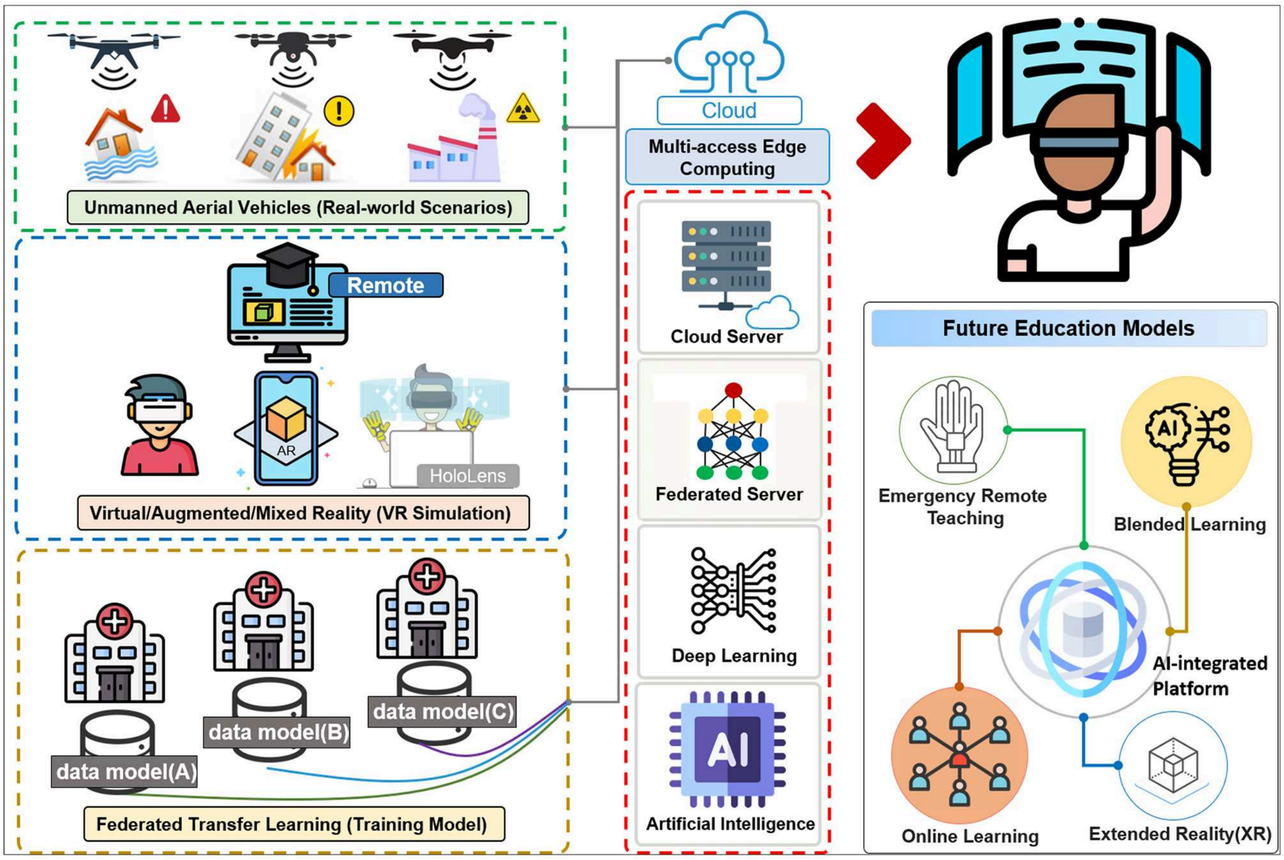

FIGURE 4
The integration of real-world scenarios with artificial intelligence technologies initiates disaster medicine remote learning (Future Education Models).

can be used to analyze large amounts of data from past disasters and identify patterns and trends that can inform future disaster management strategies. They can also be used to develop more accurate simulations and prediction models, which can be used to train students and prepare them for real-world scenarios.

Integrating and applying these new technologies can also enable new educational models, such as remote learning and online teaching, which can increase access to disaster management education and make it more convenient and flexible for students. Overall, the use of technology in disaster management education can significantly enhance students' learning experiences and prepare them more effectively for real-world scenarios.

Discussion

Blended learning in DM education has been implemented significantly by undergraduate medical or paramedic students and applied widely by clinical professionals. The occurrence of the COVID-19 global epidemic has significantly precipitated the progress and implementation of integrated hybrid (including station rotation, simulation, and distance models) learning in higher education and also in DM education (30, 39). Implementing special epidemic training for medical students, such as COVID-19 pandemic simulated programs, could significantly improve their preparedness, knowledge, and skills when dealing with emerging infectious diseases (114). The use of IoT, social media, UAVs, and advanced machine learning is not only engaging in rapid response, management, and risk reduction in disasters (DRR; e.g., Sendai Framework for Disaster Risk Reduction 2015–2030) but also stressing the important governance challenge of multidisciplinary, transdisciplinary, and interdisciplinary teaching courses on DRR implemented in many universities (115). The remote e-learning DM programs appear to be a crucial concern, and medical schools in vulnerable regions such as Asian countries or low- and middle-income countries, as we previously indicated, need to continue teaching emergency medicine (10, 33). The inability of these countries to afford state-of-the-art technologies (such as VRS-VR or AR) or to have a convenient AI network prevents medical students from using AI to further medical education. In addition to multidisciplinary approaches used in DRR, more inclusive curricula, a theoretical emphasis, a field orientation, and skill development appear to be essential for higher education. However, due to the popularity of AI-enhanced remote learning modalities among medical school students, it is important for faculty to be well-versed in online learning techniques, e-Learning tools, and cutting-edge technology (such as HoloLens) before classes. The new disruptive technologies based on integrated AI, big data, blockchain, and VR/AR could enrich teaching formats and provide broader guidance for faculty resource allocation in pedagogical methods (19, 115). Our review focuses on the application of remote technology in DM education rather than discussing the educational methods or content of different trainee levels. However, strict quality assurance methods (such as Quality Matters) (116) and continuous quality improvement (CQI) should be closely observed to enable faculty to quickly adjust to changes under the guidance of well-defined implementation plans (115).

We evaluated UAV-enabled MEC with 3-D imagery and found it useful for a variety of detection techniques in remote or disaster rescue operations. However, some restraints on the UAV during operations exist, e.g., the huge operational expenditure to maintain its infrastructural nodes or battery endurance for longer aerial communication. A "UAV-enabled wireless powering IoT" (Ue-WPIoT) with smart trajectory information of UAVs and an AI-deep learning model was developed to overcome the limitations and was designed for the consideration of more lightweight UAVs (14). The improvement of Ue-WPIoT could allow trainees more time to become familiar with the new device and fulfill the IoT wireless function in the air. In addition, a new system called the Aerial Remote Triage System has changed how MCI triage is usually done so that life-saving interventions and transportation can happen more quickly (117).

With the development of telecommunication technology, the fifth generation (5G) remote network significantly increased the band and the speed of data transmission, which was very helpful for long-distance medical diagnosis. In the field of DM, telemedicine benefited from remote devices related to research that were popular before the pandemic COVID-19. Remote learning-related research became the hottest study topic for conducting medical education corresponding to the COVID-19 isolation policy. Based on the well-established communication infrastructure and rapidly progressing telecommunication technology, we anticipate that future research will focus on the application of wearable devices in fields such as medical care and monitoring, educational instruments, and emergency rescue training programs.

The Internet of Things has been formulated to establish wireless sensor networks, AI-enhanced monitoring, and smart embedded devices (ex. in UAVs) to facilitate crowd-sourcing (CS) communication, IoT-based Early Warning System (IoTEWS), efficient victim localization (RFID tag and topology preserving maps), data analytics, and knowledge aggregation (effective data mining of collected big data) in disaster management (118, 119). Moreover, the concept of the Internet of Everything (IoE) or even the Internet of Nano Things (IoNT) was built to account for everything that could be connected to the Internet, i.e., it facilitated the connections among people, processes, data, and things ("four pillars"). The IoE provides the potential to analyze millions of connected sensors' data in order to aid automated- and people-based processes. The application of IoE could provide a remote platform by the expansion of CC to connect "everything" online with the implementation of machine-to-machine (M2M), machine-to-people (M2P), and people-to-people (P2P) (120). The concept of IoNT is being extended from IoE to achieve nanoscale networks by embedding nanosensors in diverse objects such as wearable medical devices and by connecting conventional microsensors to nanonetworks (121). Using nanodevices embedded in the environment and medical equipment, the IoNT supports computing for end users to improve in-time data monitoring and early disease diagnosis. Moreover, the IoT could provide positive implications for computer science education by reshaping web programming, tremendous excitement from online teaching, and real-world sensing applications, performed by UK Open University according to IoT principles in remote lessons for more than 2000 students in 2012 (120, 122).

Our review indicates that the newly emergent information technologies, including IoT, Big Data, social media, and machine learning, could facilitate DM tasks in visualizing, analyzing, and predicting disasters and improve the resilience of communities (123–125). Using Big Data Analytics tools and social media data mining (e.g., large-scale satellite imagery data mining) could empower all sectors, from citizens to community, government to non-government organizations, effective remote communication networks, and knowledge graphs. Remote technologies could also provide an integrated conceptual approach to higher education, such as in massive open online courses (MOOCs) or Flipped Classroom (126, 127). However, the AI innovation in DM education programs did not turn out as planned (44, 89, 128). To address the various ways in which medical students and instructors learn and receive feedback from customized lessons, more AI-guided learning pathways need to be developed. Furthermore, assessing the effectiveness of AI teaching modality and their progress in AI technologies, such as IVR, also require AI-mediated pathways (129).

As previously stated, immersive HMDs have many beneficial potentials in disaster scenarios, and there has been a lot of research interest in DM education program applications (23). VRS technologies, especially VR devices, are widely incorporated into education, teaching, and training in various application domains. VRs are useful for many aspects of "soft" skills acquisition, such as cognitive skills, spatial and visual information, visual scanning or observational skills, and affective skills related to controlling emotional responses to stressful or difficult situations (130). Moreover, VR, MR, or HoloLens, *via* visualizing 3D anatomies, could provide medical training programs, such as surgical technique, catheter placement, or cardiopulmonary resuscitation (131–133). The VRS technologies can also create disaster scenarios based on real-world events, and inexperienced students could learn the details of disaster response without being in dangerous situations. Although many authors treated VR or HoloLens as promising learning tools for higher education, only some design-oriented studies based on systematic target theories are constructed (23). Although the procedure- or practice-oriented content, i.e., realistic surrounding teaching environments, made HMDs more exciting and appealing, the actual usability and performance of students using HMDs remained primarily experimental. Only 2.6% of a scoping review study revealed that conceptual frameworks or theories were designed in medical students' VR education (131). Finally, when considering the use of HMDs, we should consider what goals are attainable with them, which technologies are predisposed to incorporate them, and what steps are required to implement them. Although most participants enjoyed and engaged in these novel techniques, realistic HMDs could not replace traditional methods for providing curriculum content in a short time (42). However, with the improvement of new HMD technologies, the wide-range web capacity, cybersickness-prevented design, and cordless HMDs, the new learning modalities will gradually reduce the technological limitations and make the new learning modalities more popular in the future.

We presented the visualized graph drawn by VOSviewer to stress the connection between various keywords, which mirrored the popular study fields and the progress changing with time. However, we have to point out that VOSviewer could not integrate the search results from different databases. The visualized graph was drawn from the literature searched on either PubMed or WES websites. Other limitations are the option methods of VOSviewer to draw the graph, which can affect the visualized result. For example, choosing the keywords defined by the author or MeSH keywords can result in a different view of the graph.

Conclusion

In this scoping review, by reviewing the state-of-the-art technologies in the last two decades, we found the potential implementation of MECs, such as UAVs combined with IoT, cloud sensor networks, and machine learning was well-suited for integration into emergency services for disaster management. In the future, DM education will be more likely to use blended AI-modulated remote learning models, such as well-developed HMD optical devices based on AI-enhanced real-world scenarios (Figure 4). Moreover, for students to learn well using remote technologies, there should be real-time individual feedback, interactive curriculum review, and AI-assessed algorithms.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

C-LK contributed to the conception and design of the study. L-CC organized the database. C-LK and C-CC reviewed all related articles and decided to include extended articles in the study. M-CW and J-ST revised the references. P-CH analyzed and drafted the figures and table. C-LS supervised the study. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpubh.2023.1029558/full#supplementary-material

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