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A systematic review

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Flood impacts on healthcare facilities and disaster preparedness – A systematic review

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A R T I C L E I N F O

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A B S T R A C T

Hydrometeorological hazards, particularly floods and cyclones, pose significant threats to human health, including fatalities, damage to healthcare facilities (HCFs), and disruptions to health services. This study systematically reviewed scientific articles to identify the direct and indirect impacts of floods on HCFs and the risk management strategies implemented to address these challenges. To that end, we searched four databases (MEDLINE, Embase, Web of Science and Scopus) for articles written in English. Our search query included terms related to flood and cyclone hazards, HCF types and disaster risk management strategies. We followed the PRISMA guidelines to conduct the study. The search resulted in 7500 records, which were finally filtered down to 74 studies after removing duplicates, screening records and full article eligibility checks. Approximately 76 % of the included studies addressed cyclone-related flood impacts and were conducted in the United States. Hospitals were the most studied HCFs (n = 54) followed by long-term care facilities (n = 11). The main impact of floods on hospitals was due to flooded basements as they house important services including equipment, supplies and backup generators. Interruptions of electricity and water supplies were reported to cause serious challenges. Regarding flood risk management, patient evacuation was mentioned by more than 66 % of the studies while few studies reported the implementation of structural measures. More than a third of the studies reported the availability of preparedness plans. The review revealed inconsistencies in the flood preparedness of HCFs. The main policy recommendations are the availability of guidelines to standardize preparedness plans and oversight.

1. Introduction

Floods are the most frequent natural hazards, significantly impacting societies. The Centre for Research on the Epidemiology of Disasters (CRED) recorded 164 flood events globally in 2023, killing and affecting more than 7700 and 32 million people, respectively [1]. The economic losses in the same year were estimated at more than US$ 20 billion. Floods have direct health impacts such as deaths, injuries, infectious diseases and mental health issues, and indirect ones such as malnutrition due to damage to crops and

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livestock, and interrupted treatment due to the inaccessibility of flooded healthcare facilities [2].

To continue providing essential health services such as medical and nursing care, dialysis services, laboratory and medicines during disasters, healthcare facilities (HCFs) must remain safe and accessible [3]. HCFs, including hospitals, long-term care facilities (LTCFs), pharmacies, and outpatient facilities such as hemodialysis (see Toner et al. [4] for the full list), are normally perceived as a source of help when disasters unfold although they can be disaster victims [5]. Recently, a flooded hospital in Tennessee, United States, grabbed headlines after stranded people were rescued from the hospital roof [6]. Hence, facilities should develop the capacity to reduce or manage flood risk and recover rapidly if affected by a flood event. They can achieve this capacity by conducting hazard and vulnerability analysis, developing a preparedness plan, coordinating with other HCFs and relevant stakeholders such as local authorities, and implementing risk reduction measures such as following building codes and safety guidelines [3,7,8].

Existing review articles have examined the impacts of disasters on healthcare, including hurricane impacts on community health and HCFs [9], disaster impacts on hospitals [10], the impact of climate-related disasters on cancer care facilities [11] and direct and indirect impacts on dialysis patient care [12]. Other articles reviewed flood risk reduction measures, including hospital evacuations [13–15], emergency preparedness in HCFs [16], hospital business continuity plans for post-disaster recovery [17], hospitals' structural and non-structural resilience to disasters [18], disaster planning of LTCFs [19], the role of primary health care professionals in disaster risk management [20], and HCFs' disaster preparedness for water supply and wastewater management [21]. Except for [9], which focused specifically on hurricane hazards, all other review articles addressed multiple hazards, primarily focusing on hospitals. While an all-hazard risk management approach is recommended (e.g., Refs. [22,23]), the frequent occurrence of floods worldwide and the unique considerations they require highlight the need for a dedicated review of the impacts of floods on HCFs and their preparedness strategies. Non-hospital facilities (e.g., nursing homes) should also be considered in such a review as they provide essential health services during emergencies.

The main objective of this systematic review is to synthesize available information on flood impacts on and preparedness of HCFs. Specifically, we aim to answer two questions: (i) What are the critical impacts of floods on HCFs? and (ii) What flood risk management measures have been adopted by these facilities? The hazard addressed in this review is flooding, irrespective of its specific type. As cyclones can lead to severe flooding due to heavy rainfalls or storm surges, we have included them in the review. However, the impact of cyclone wind on HCFs is not the focus of this study. Regarding the measures, we considered measures implemented at all phases of flood risk management [24]: prevention, preparedness, response and recovery.

2. Methods

2.1. Search strategy and selection criteria

Four electronic databases were searched for this systematic review: MEDLINE ALL, Embase, Web of Science Core Collection and Scopus. We designed the search strategy with a biomedical information specialist, who performed the literature search on November 20, 2023. The search included all available records in the four databases until the search date. The search terms were grouped into three categories. The first category is related to the flood and cyclone hazards, including some notable events such as Hurricane Katrina, and the associated disasters. The second category is about healthcare facilities including hospitals, LTCFs, dialysis centers and pharmacies. The last one concerns disaster risk management, including the different phases and associated strategies. We provided a summary of the search strategy in Table 1 and the complete query for each database in Appendix A. The search query contains only English words and filters out documents not written in English. We also limited the document types to articles to reduce irrelevant search results, excluding document types such as book reviews, corrections and data papers. We did not identify any new studies via other methods such as websites and citation searching.

After removing duplicates, two authors (YAA and MP) independently screened the resulting records using Rayyan (https://www.rayyan.ai/), an online platform that facilitates a systematic review. YAA screened all the records while MP randomly screened 50 % of the records. The authors resolved disagreements by consensus. The inclusion criteria include the presence of one of the hazards and their impacts primarily on HCFs and the presence of disaster risk management strategies before, during or after the natural hazard. We excluded records that.

Table 1
A summary of terminologies used in the search queries.

Hazard	Healthcare facilities	Disaster risk management
Flood	Health(care) facility	Preparedness
Cyclone	Hospital	Planning
Hurricane	Nursing home	Mitigation
Typhoon	Care home	Recovery
Tropical Storm	Assisted living facility	Response
	Pharmacy	Adaptation
	Clinic	Resilience

Note: Terms within each category were connected using the OR operator (e.g., Flood OR Cyclone OR Hurricane OR Typhoon or Tropical storm). The three categories were combined using the AND operator, i.e., Hazard AND Healthcare facilities AND Disaster risk management.

- focus on COVID-19 or other hazards such as earthquakes, tornadoes or fires
- address general public health issues such as disease outbreaks and mental health concerns
- focus specifically on the impacts on residents or medical staff rather than on HCFs
- discuss broader disaster risk management topics
- discuss animal studies
- are review articles
- do not include an abstract

After screening, YAA retrieved and assessed full-text reports for eligibility. Reports were excluded during the full-text eligibility check if they: (i) contain no or insufficient description of disaster risk management practices or flood impacts on HCFs, (ii) focus on health impact assessment, especially public health issues, (iii) focus on governance or management aspects, (iv) focus on modelling such as evacuation modelling, road network modelling and accessibility issues and exposure mapping, (v) are not related to flood or hurricane hazards or floods that are not caused by hydrometeorological events (e.g., pipe burst), and (vi) are review articles.

2.2. Data analysis

YAA extracted data from eligible studies. Data were collected on.

- the record – publication year, and country of study
- the study – hazard type including event name if specified, HCF type including facility name if specified
- reported impact – damages to facility buildings, patient death or injuries, interruption of utilities, interruption of health services and financial losses
- reported risk management strategies – flood mitigation, management and recovery measures including evacuation and shelter in place, structural/permanent measures, temporary measures, availability of disaster preparedness plans and insurance.

It should be noted that data collection is based on what is reported in the selected studies. For example, studies may not mention all

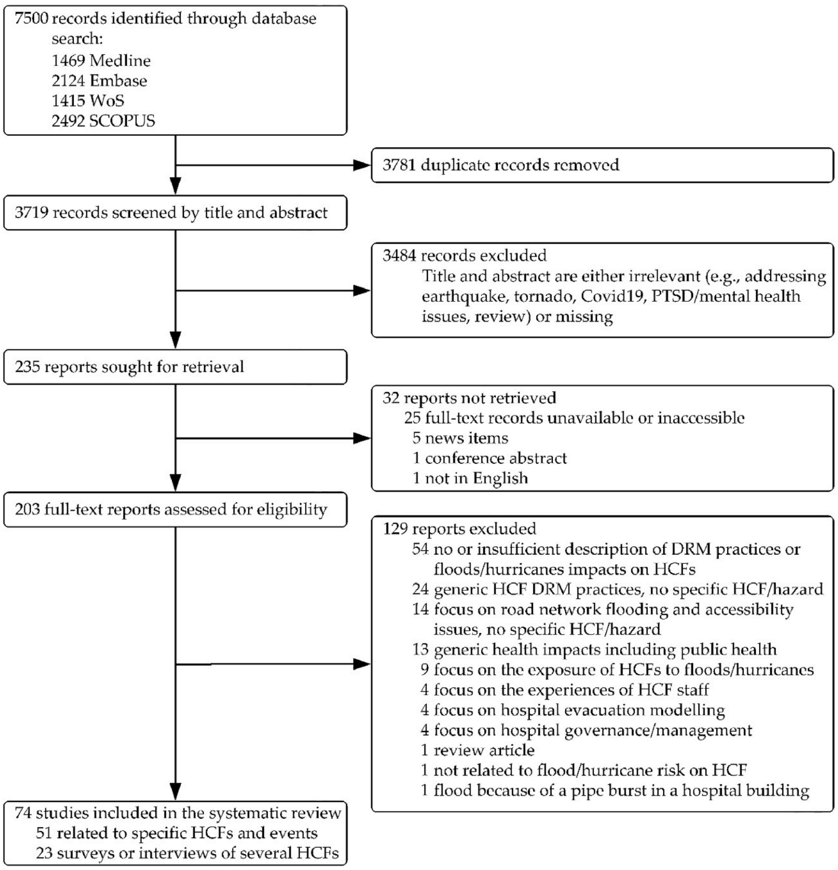

Fig. 1. A PRISMA 2020 flow diagram for the study selection. DRM = disaster risk management; HCF = healthcare facilities.

available flood risk management strategies that an HCF implemented. We used Microsoft Excel to tabulate the reports based on the above thematic categories and variables. When possible, we used descriptive statistics to summarize the collected data. Otherwise, we described the results narratively. Our search strategy, study selection and data analysis were conducted following the PRISMA 2020 guidelines [25].

3. Results

3.1. Characteristics of included studies

Searching the four databases identified 7500 records (see Fig. 1 and Table A1). After removing duplicate records, we screened 3719 records. Of those, 235 reports fulfilled the inclusion criteria and were sought for retrieval. Twenty-five full-text reports were unavailable or inaccessible while seven records were not retrieved because either they were news items, conference abstracts or not written in English. We assessed the eligibility of 203 full-text reports and included 74 studies for the review. Fig. 1 shows the complete literature search and screening steps with the associated results. Moreover, Appendix B summarizes the key characteristics of all the included studies. The non-duplicate records, the reports sought for retrieval (including exclusion reasons) and the final included studies (including key characteristics) are available in Ref. [26].

Among them, 51 studies are case reports describing flood impacts on specific HCFs and their preparedness and responses, whereas 23 studies conducted qualitative, quantitative or mixed research that included a range of HCFs and respondents. For example, Castro et al. [27] involved 217 LTCFs, and Irvin-Barnwell [28] studied 64 hospitals and 186 healthcare centers. Fig. 2(a) shows that most of the included studies addressed flood impacts from cyclones (n = 56), of which most are associated with one of the following: Tropical Storms Alberto (1994) and Allison (2001), Hurricanes Floyd (1999), Harvey (2017), Hugo (1989), Ike (2008), Irene (2011), Irma (2017), Ivan (2004), Juan (2003), Katrina (2005), Maria (2017), Matthew (2016), Rita (2005) and Sandy (2012) or Cyclones Tracy (1974) and Yasi (2011). The most studied hurricane in the included reports is Katrina (n = 13), followed by Sandy (n = 9) and Rita (n = 7). Seven studies described the impacts of and lessons learned between two hurricanes: Irene and Sandy ([29,30]), Irma and Maria ([31]), Katrina and Rita ([32,33]), Katrina and Gustav ([34]), and Rita and Ike ([35]). On the other hand, three studies could not be associated with a specific hurricane: (a) Brands et al. [36] discussed a hospital's disaster preparedness considering its vulnerabilities to previous hurricanes; (b) Brown et al. [37] surveyed LTCFs hurricane response and recovery, which was not specific to a single,

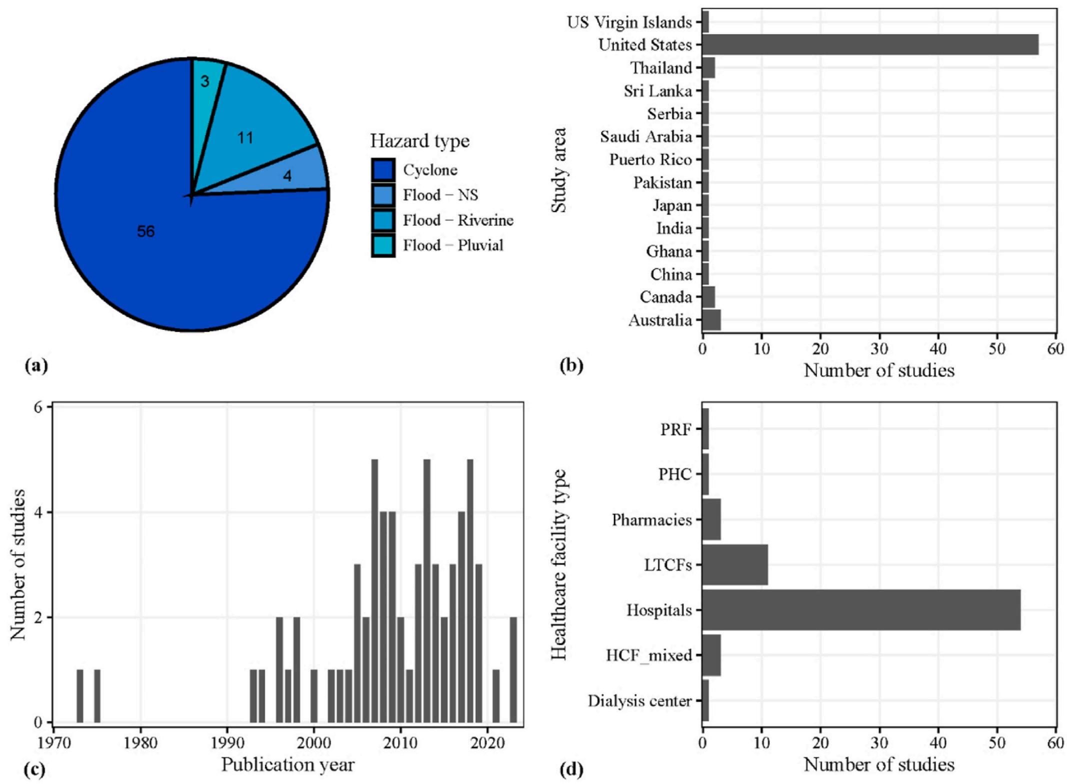

Fig. 2. Studies included in the review per (a) hazard type, (b) study areas, (c) year of publication and (d) HCF type. Puerto Rico and US Virgin Islands are unincorporated organized territories of the United States with local self-government. "HCF_mixed" denotes studies that included more than one HCF type. US = United States, NS = Not specified, PRF = post-acute rehabilitation facility; PHC = primary health center; LTCF = long-term care facility; HCF = healthcare facility.

particular hurricane; and (c) Henkel and Marvanova [38] conducted a study with no relation to a specific hurricane event, although the research was motivated by the impact of previous hurricanes. Furthermore, 18 studies described the impacts of riverine ([5,39–48]), pluvial ([49–51]) and other unspecified ([52–55]) floods on HCFs.

Most of the studies were conducted in the mainland United States (n = 57), as shown in Fig. 2(b). Three studies were from Australia and two studies each were from Canada and Thailand. There was one study each from China, Ghana, India, Japan, Pakistan, Puerto Rico, Saudi Arabia, Serbia, Sri Lanka and US Virgin Islands. Two studies were published in the 1970s while the rest were published in 1993 and beyond, as shown in Fig. 2(c). The number of studies increased after the 2005 Atlantic hurricane season, especially related to the impact of Hurricane Katrina in the United States.

Fig. 2(d) shows hospitals were the most studied HCF (n = 54). The whole Texas Medical Center was the focus of three studies ([56–58]), while three other reports also studied specific hospitals located at the Texas Medical Center: Memorial Hermann Hospital ([59,60]), Memorial Hermann Children's Hospital ([60]) and Lyndon Baines Johnson General Hospital ([61]). Those hospitals were affected by Tropical Storm Allison and Hurricane Harvey in 2001 and 2017, respectively. The second most studied HCFs were LTCFs (n = 11), and the rest were pharmacies (n = 3), a dialysis center, a primary health center and a post-acute rehabilitation facility. Three other studies included more than one HCF type: hospitals and primary medical care units ([54]); hospitals, clinics and pharmacies ([47]); and hospitals and healthcare centers ([28]).

3.2. Reported impacts

Floods have direct impacts on HCFs by causing damage to the buildings and their contents such as medical equipment. Table 2 summarizes the main flood impacts reported in the included studies. We highlighted the implications of flooded hospital basements, which were reported by several studies. Floods can also cause patient death and injury, and major disruptions to the services provided by HCFs when they interrupt utility, such as electric power, water supply and telecommunication. Such direct and indirect impacts of floods may force HCFs to close at a time when they are needed most. Finally, the mentioned impacts have financial consequences for HCFs, which can be resolved by risk-sharing mechanisms such as insurance, or with the support of relevant government entities. We divided the reported impacts into: direct damages (Section 3.2.1), interruptions of utilities (Section 3.2.2) and healthcare services (Section 3.2.3), and other impacts (Section 3.2.4).

3.2.1. Direct damages to facilities

Almost one-third of the included studies reported that hospital basements (Fig. 3(a)), which housed vital services, were flooded and caused major disruptions ([5,29,39,42,43,48,49,51,56–59,62–72]). For example, a pharmacy, laboratory, information services, data center, supplies and distribution center located in the basement of a hospital were flooded, and the facility had to evacuate patients and close for months [39]. Fang et al. [56] and Sirbaugh et al. [58] also reported that interconnected basements of hospitals within the Texas Medical Center in Texas, United States, flooded in 2001 causing damage to equipment, laboratories and morgue. Thus, the hospitals lost primary and backup electrical systems and water supply, which forced them to evacuate patients and close. Pumps located in Bellevue Hospital Center's basement failed when the basement was flooded due to Hurricane Sandy in New York, United States, and their failures seriously affected water and fuel supplies [70]. Thirty-two elevators in Bellevue became non-functional after the elevator shafts in the basement were inundated [69]. In another case, the flooding of a cafeteria located in the basement of a hospital created a shortage of food supply [63]. Simbawa [49] emphasized that a flooded morgue in a hospital basement caused disruptions to the hospital service as drowned victims were brought to the facility.

Flooding of other floors (i.e., above ground) of HCFs also caused serious damage such as damage to expensive medical equipment at hospitals [55,58,65,75], physical records at pharmacies [76], LTCFs [89] and hospitals [67,87]; and emergency and equipment rooms [85]. The ground floor of a dialysis center in New Orleans was flooded during Hurricane Katrina causing extensive damage to an elevator, electrical boxes and mechanical equipment, which required replacement [84]. Garages and parking lots could also flood [60], hampering evacuations, staff and patient movement and delivery of supplies.

Among all the studies, only two explicitly mentioned patient deaths at hospitals. Gray and Hebert [66] reported the death of 72 patients at three hospitals related to Hurricane Katrina although some might have died before the hurricane. Taylor [72] also reported the death of two patients during an evacuation from a hospital because of Katrina. Similarly, only two studies explicitly reported deaths at LTCFs: (a) 35 nursing home residents drowned due to Katrina [89], and (b) seven residents of nursing facilities and large assisted

Table 2
The main reported flood impacts on HCFs.

Impacts	Studies
Direct damages due to flooded basements	[5,29,39,42,43,48,49,51,56–59,62–72]
Direct damage due to flooding at above-ground floors	[27,28,30,31,35,44,45,47,50,52,54,55,58,60,61,73–90]
Power outage	[5,28,29,31,32,37,40,45–51,54–56,58–60,62–80,82,83], [85–87,91,92]
Interruption of water supply	[28,40,42,44–46,48,55,56,59,60,63–70,73,75,78,79,83,85–87]
Interruption of telecommunication services	[28,29,37,40,43,46,48,54,59,60,62,63,65–67,75,77–79,82–84,86]
Inaccessibility of HCFs due to flooded roads	[47,57,58,61,78,81,85,87,93]
Financial/revenue loss	[27,44,62,76,90,94]
Patient deaths	[27,66,72,89]
Mental distress and physical injuries	[32,34,78]

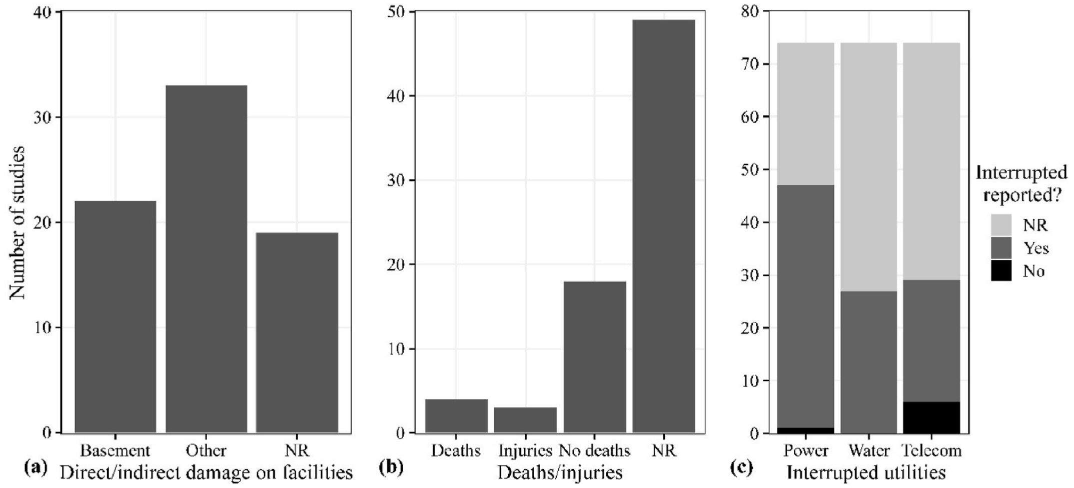

Fig. 3. Summary of some flood impacts reported in the included studies. (a) shows the number of reported flooded basements and other parts of HCFs as a proxy for direct damage to facilities. (b) shows the reported deaths and injuries, and (c) presents the reported utility (power, water and telecommunication) interruptions as an indirect impact of floods on HCFs.

living facilities died related to Hurricane Rita [27]. Some studies mentioned patients' mental distress and physical injuries due to LTCF evacuations ([32,34]) or bad conditions at a hospital ([78]). As shown in Fig. 3(b), other studies explicitly reported that there were no serious patient injuries or fatalities either during evacuations or due to direct damage to hospitals ([29,30,40,45,50,60,62,64,65,67,80,87,90,93,95–97]) and LTCFs ([83]).

3.2.2. Interruption of utilities

The interruption of utilities (Fig. 3(c)) posed a significant threat to the functioning of HCFs. More than 60 % of the selected studies reported power outages. As electric power is essential for light, air conditioning, elevators, computers, laundry facilities, medical equipment including life support, and refrigeration, its interruption proved to be the most important decision parameter in facilities response strategies. For example, Brevard et al. [63] reported that the unavailability of lights and elevators posed a considerable challenge in the 19-stories Charity Hospital in New Orleans after Hurricane Katrina caused a power loss. Hospital staff had to deliver water, food and fuel supplies and carried patients to evacuation stages using stairs. Power outage due to Tropical Storm Allison in Memorial Hermann Hospital in Houston, United States, also interrupted several vital functions such as electrical ventilators, laboratories, pharmacy, elevators and escalators [59]. In the case of Ocean Springs Hospital in Mississippi, United States, an air conditioning system was not functional after a power outage due to Hurricane Katrina [77]. The high temperature in the facility created uncomfortable conditions for staff and patients, and laboratory equipment also malfunctioned. Similarly, because of a flood-related power failure in Mabi Memorial Hospital (Japan), malfunctioning air condition worsened elderly patients' health condition, and it was not possible to retrieve patient records as computers were down [45]. The anticipation of electric failure might even lead to evacuation [5]. Power loss did not only determine evacuation decisions but also the reopening of facilities and when to bring back evacuated patients [82]. Power outages also forced several pharmacies to close ([76,91]).

Lack of water supply, which was reported by 35 % of the included studies, also created serious challenges to hospital services such as surgeries and overall care [46,87], the use of toilets [63,78] and keeping basic hygiene [59,79]. Due to the interruption of clean water because of flooding, a hospital conducted emergency surgeries using bottled water [40]. In one case, a hospital that was not directly flooded had to evacuate patients after a sewage facility connected to the hospital and surrounding areas including access roads were flooded [42]. Interruption of telecommunication services such as landlines, mobile networks and internet created communication hurdles, especially if the flood duration is long and capable of isolating the facilities [78]. Furthermore, being unable to communicate with relevant (non)governmental entities and other hospitals may hinder on-time support [45,67]. Nevertheless, no study reported that HCFs made major decisions because of loss of communication.

3.2.3. Interruption of healthcare services

HCFs often provide reduced services just before or after being flooded. Hospitals canceled scheduled surgeries (e.g., Refs. [5,40,41,46,74]), and most facilities discharged patients, especially if the HCF evacuated. In other cases, facilities closed and provided no healthcare services for a couple of days (e.g., Refs. [51,94,95]), weeks (e.g., Refs. [42,50]) and more than a month (e.g., Refs. [29,39,59–61]). Arya et al. [76] reported that 66 % of the pharmacies they surveyed took less than a month to reopen after a hurricane while around 20 % and 8 % took less and more than six months, respectively. In another case, severe flood damage to a post-acute rehabilitation facility forced the management to lease a different location for several weeks to resume service [35]. Levinson [67] also reported that a hospital severely damaged by Hurricane Sandy was still closed for about a year when the study was conducted. When facilities sustain significant damage, such as a dialysis center that Hurricane Katrina compromised [84], a major renovation was necessary. In the worst cases, facilities had to close permanently as they were severely damaged and renovation was not viable. Three studies reported the permanent closure of HCFs (i.e., Jiang et al. [83] – two LTCFs; Taylor [72] – two hospitals; and Irvin-Barnwell et al. [28] – three healthcare centers).

3.2.4. Other impacts on facilities

Flooded streets around HCFs could obstruct transportation creating staff shortages ([58,85]), limiting supplies ([57,78,81,93]), limiting accessibility and help to facilities ([50]) and forcing ambulances to reroute ([85]). In some cases, such impacts could last several days. For example, surrounded by flood for five days, a hospital was inaccessible to potential patients and hospital staff, and supplies could not be delivered [61]. Floods could also damage or hamper the accessibility of external warehouses affecting supplies [47,87].

Another indirect impact of floods on HCF was financial loss, which can be related to revenue loss because facilities closed and additional expenses for evacuations and overtime payments of staff. Such losses could reach tens of millions of US dollars per hospital ([44,62,90,94]). Castro et al. [27] reported that 80 % of nursing facilities and 64 % of assisted living facilities experienced financial losses due to evacuation costs and reduced donations. The majority of pharmacies that participated in a survey conducted by Arya et al. [76] stated revenue loss.

After flood disasters, HCFs suffer from a staff shortage. About a third of the hospitals that participated in a study by Levinson [67] indicated staff shortage, while Burger and Canton [79] reported shortage of nurses. The reasons for staff shortage include road closures and transportation challenges ([67]), issues of family safety ([85]) and when evacuated staff could not return because of damaged houses [79].

3.3. Flood risk management measures

We extracted and analyzed different flood risk management strategies implemented by HCFs (Table 3). We categorized these strategies into four groups: evacuation (Section 3.3.1), shelter in place (Section 3.3.2), structural and temporary measures (Section 3.3.3), and disaster preparedness plans and insurance (Section 3.3.4). Evacuations may occur before an event or any time after the event starts (e.g., after a facility or its access roads are already flooded). Moreover, we did not account for early discharges of patients to their houses as evacuation. Structural measures are measures that are permanently installed within the facility building or its surroundings (e.g., floodgates and permanent flood barriers), while temporary measures are movable measures that will be removed (e.g., sandbags) or restored to their original position (e.g., moving equipment to higher floors) after the event.

3.3.1. Evacuation

About 66 % of the included studies mentioned patient evacuations as a flood risk reduction measure (Fig. 4(a)). Some studies reported that HCFs evacuated patients before a flood occurred [30,35,62,64,75,88,90,93–97]. Others mentioned that patients were evacuated after the event [5,31,39,42,44,45,48,50,51,56,58–60,65,66,69,70,72–74,78,79]. Five studies reported patient evacuations from different facilities before and after the event [29,33,34,67,68]. The rest did not specify when the evacuations took place. Most HCFs evacuated before the event because of mandatory evacuation orders [29,30,44,62,90,93,95,97]. Castro et al. [27] also showed that the majority of evacuated LTCFs did so because of mandatory orders. However, mandatory evacuation orders do not always result in the evacuation of all facilities. For example, among the 3112 LTCFs studied by Peterson et al. [98] in Florida, United States, 408 were located within the mandatory evacuation zone, and only about 52 % evacuated during Hurricane Irma although that was a higher percentage compared to the facilities that evacuated but were not under mandatory evacuation order. On the contrary, Gray and Hebert [66] reported that hospitals were excluded from mandatory evacuation during Hurricane Katrina, but most had to evacuate when conditions deteriorated. Hospitals that historically receive patients during storms also do not tend to evacuate in advance [66].

Regarding prioritizing patients for evacuations, some hospitals evacuated their most critical patients first [29,41,51,59,60,63,64,69,72,73,78,94,97], whereas others evacuated critical patients last [30,44,45]. In the latter case, the reason could be the availability of evacuation resources such as means of transport [45] as critical patients may need air or land ambulances with special equipment, which may not be readily available. Claver et al. [32] highlighted the dilemma of prioritizing LTCF residents' evacuation where facilities made different decisions regarding when to evacuate the sickest residents. One facility had to decide to evacuate the most fragile residents last as it was difficult to secure suitable transportation for those residents when situations worsened because of a hurricane. In contrast, Levinson [67] reported that one hospital evacuated less critical patients while sheltering the most critical ones in place.

Table 3
The main reported flood risk management measures HCFs implement.

Flood risk management measures	Studies
Evacuation	[5,27,29–35,37,39,41,42,44,45,48,50,51,56,58–60,62–70], [72–75,78,79,82,83,85,88,90,92–98]
Shelter in place	[27,30,32–34,37,40,67,68,80,82,83,87,89,92,98]
Disaster preparedness plans	[27,29,33,35–38,40,42,50,52,56,63,65,68,69,77,78,80,83,89,90,92,94–96,98,99]
Availability of backup generators	[5,28,29,33,36–38,40,42,45–47,49,50,53,54,56,58–60,63–72], [74–80,82,83,86,87,89,91,92,96,97]
Structural (permanent) measures	[36,39,56–58,75,81]
Sandbags	[5,30,41,42,64]
Pumping out flood water	[5,51,69]

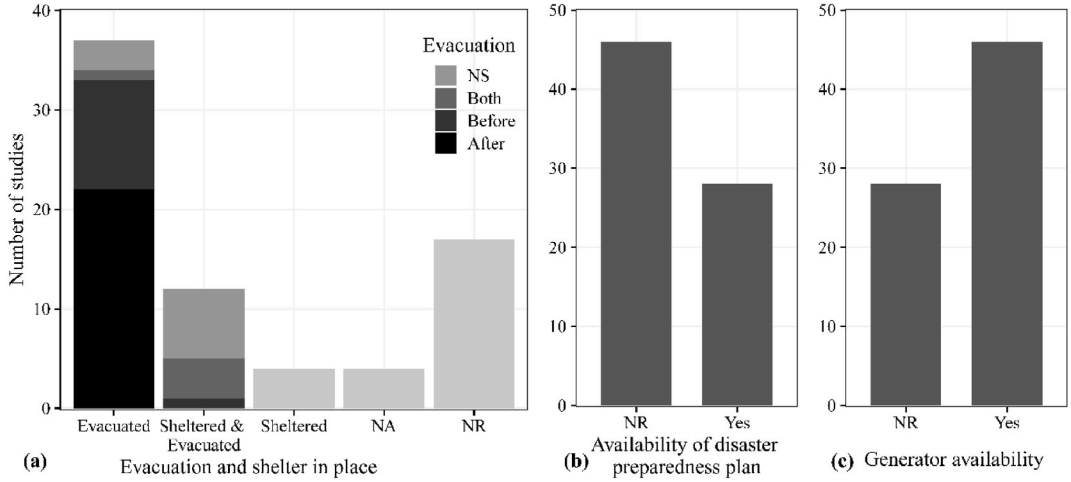

Fig. 4. Summary of flood risk management measures reported in the included studies. (a) shows the number of studies that reported evacuations (before or after a flood event, or both). Some studies did not specify (NS) when the evacuation occurred, while evacuation does not apply (NA) to pharmacies and dialysis centers. (b) and (c) show the number of included studies that reported the availability of disaster preparedness plans and backup generators, respectively. Some studies did not report (NR) any of the measures.

Concerning the means of transporting patients during evacuation, ambulances, buses and helicopters were the most common ones. In some cases, boats ([45,50,63,65,78]); kayaks ([51]); transport, military or commercial airplanes ([42,44,73,93,95,97]) and military or other large trucks ([39,42,44]) were used for evacuation. Most of the studies utilized a combination of the above transportation means based on their availability, patients' condition and severity of the flood. Another crucial element regarding HCFs evacuation is the availability of receiving facilities. Some studies emphasized HCFs sharing the same parent corporation benefit from the corporate structure that prioritizes patient evacuation within their facilities ([30,32,51,58,88,95,96]). Other benefits of patient transfer within facilities run by the same organization include the possibility of transferring all patients to one facility and ease of access to medical records. Such arrangements are especially important when several major facilities need to evacuate at the same time [58].

With experience, facilities might improve their evacuation practices. For example, one facility revised its emergency preparedness plan after identifying deficiencies during an evacuation related to Hurricane Rita [35]. Changes included selecting a better evacuation site, purchasing a utility trailer to transport equipment and supplies, identifying primary and secondary evacuation routes and enhancing communication systems. These improvements contributed to a smoother evacuation during Hurricane Ike. In another study by Blanchard and Dosa [34], five nursing homes sheltered in place during Hurricane Katrina while nine evacuated before the storm and six after. However, 16 of those facilities participated in the study after Hurricane Gustav indicated that all evacuated before the storm. Most nursing homes experienced better collaboration with state authorities, including assistance with patient transport. Despite improvements compared to Katrina, 44 % of the nursing homes still faced transportation or sheltering problems during Gustav, which occurred three years after Katrina.

On the other hand, facilities may face difficulties even having prior evacuation experience. For example, one hospital evacuated all patients before Hurricane Irene in coordination with relevant government agencies although the hurricane's impact on the facility later was minimal [30]. However, considering the logistical challenges of evacuating hundreds of patients, the hospital's management decided to evacuate only critical patients before Hurricane Sandy while the remaining patients sheltered in place. That decision was problematic as Sandy posed more serious flooding issues to the facility. Similarly, another hospital's evacuation experience during Irene helped management assess the capabilities of regional hospitals to accept patients, as well as understand the logistics of evacuating patients, staff, and equipment [29]. However, because of the mandatory shelter in place orders from government authorities before Sandy, the hospital encountered greater challenges during the emergency evacuation once the hurricane impacted the facility.

HCFs reported several challenges during evacuations, such as.

- delayed ambulances and transport buses due to road closures enforced by police [90] and road congestion due to the evacuation of residents at the same time as the evacuation of a facility [35,66,94,95].
- documenting patients' transfers [59] and difficulties in providing patients' medical information [29] to receiving facilities due to the inaccessibility of computers and electronic medical records
- logistical challenges in terms of medical records, medications and equipment required [93].
- unavailability of enough vehicles to transport patients, equipment, medicines, medical records and supplies [33,35].
- difficulty tracking and communicating with patients during their evacuation journey [94,97].
- communication issues between and among staff and families during or after evacuations [35,66,94].
- scheduling and coordination issues of helicopter flights [78].
- shortage of space because facilities agreed to accept evacuating patients from several locations [82].

- evacuating special groups of patients such as behavioral health and neonatal intensive care patients and lack of nearby facilities with the same care unit [29,30,66].
- sanitation issues and unavailability of enough food [73].

3.3.2. Shelter in place

Four studies reported full shelter in place of HCFs [40,80,87,89]. However, Ramsey [40] reported internal relocation within a hospital to utilize resources better. Campese [80] highlighted that a hospital did not evacuate because the predicted hurricane path aligned with the hospital's evacuation route. Additionally, the hospital management considered the potential of heavy traffic from evacuating residents of the surrounding area. The hospital also relocated patients from higher floors because of the potential window damage and leakage experiences. Twelve other qualitative/quantitative studies reported both shelter in place and evacuation of the facilities they studied [27,30,32–34,37,67,68,82,83,92,98].

As in the case of mandatory evacuations, HCFs may shelter in place due to mandatory orders. Jarrett et al. [30], Jiang and Tedeschi [82] and Espiritu et al. [29] highlighted that although authorities ordered mandatory evacuations of hospitals in New York, during Hurricane Irene, they ordered a shelter in place for HCFs during Hurricane Sandy. One of the reasons given by the authorities for ordering HCFs to shelter in place was the perceived risk of evacuating patients [82,83].

3.3.3. Structural and temporary measures

Seven studies reported structural risk reduction measures at HCFs. A notable set of measures is the one at and around the Texas Medical Center (TMC), which had been affected by several tropical cyclones including Tropical Storm Allison and Hurricane Harvey [56–58,81]. After Allison, TMC increased its flood design standard from a 100-year to a 500-year return period. To attain the higher protection level, the measures implemented include improving the drainage system around TMC such as widening a stream and constructing stormwater detention facilities, installing watertight flood doors and gates, constructing floodwalls and other barriers along TMC's perimeter, elevating roads to allow access to and from the facilities, constructing sky bridges, relocating electrical equipment to upper floors, building additional electricity backup stations and installing telecommunication towers on the roofs of garages.

Another Texas hospital also built vaults with water-tight doors to protect expensive equipment from future floods, raised utilities by about 6m and raised a new hospital building's floor level by more than 3m above mean sea level [75]. Learning from the experiences of hospitals in Florida a newly built hospital housed mechanical equipment on the fourth floor in a fortified space with no windows and built sealed fuel tanks and a helipad that could accommodate military-grade helicopters [36]. Another example of a structural measure is the repurposing of a hospital basement into an innovation center, where staff meet and discuss innovative ideas to improve healthcare services, after a major flood damaged the basement [39].

Five studies reported the use of sandbags to prevent or reduce flood impacts [5,30,41,42,64]. A hospital also built temporary clay dikes after river water overtopped permanent dikes [44]. Other measures include pumping flood water out ([5,51,69]), placing medications on higher shelves, and sealing and reinforcing pharmacies temporarily ([76]), locating hospital information systems outside facilities ([65]), arranging off-site data backups ([36,38]), relocating movable equipment to a higher floor ([47]), placing generators on higher floors and letting the ground floor inundate while providing care on higher floors ([53]). Placing hospitals on higher grounds is also an important flood risk management strategy [40].

3.3.4. Disaster preparedness plan and insurance

Several studies reported the availability of disaster/emergency preparedness plans (see Fig. 4(b)) although some facilities had more adequate disaster plans than others and specifically addressed hurricane and flood hazards. In some cases, such plans were a requirement for licensing and should be approved by authorities annually [98]. However, in a study conducted in Sri Lanka, only four among 31 HCFs had disaster preparedness plans and only one facility practiced the plan within a year before the study was conducted [54]. Similarly, a study in Thailand showed that none of the 24 participating hospitals satisfied all elements of a disaster preparedness plan – planning, organizing, training, exercise and evaluation [52].

Some HCFs had flood/hurricane-specific disaster plans (e.g., Refs. [83,90,95]). Disaster plans could also elaborate an HCF's evacuation plans. For example, a hospital had an evacuation plan for Category 3 or stronger hurricanes, including to which receiving hospital different groups of patients evacuate [95]. Additionally, such plans could consider an early arrangement of transportation services for evacuation purposes [42]. However, the plan could be insufficient if the transportation company has limited options, for example, only one van [89]. Organizing evacuation drills is another element of the plan although there is no standard for the frequency and type of the drills. For example, Seale [35] reported a biannual rehearsal including staff and patients. In a study conducted by Levinson [67], 172 hospitals reported conducting at least one simulated or actual emergency exercise a year before Hurricane Sandy.

Disaster preparedness plans should also address the availability of alternative energy, water and communication sources. In this review, approximately 62 % of the included studies reported the availability of generators as an alternative energy source during power outages, as shown in Fig. 4(c). The availability of generators can also be a requirement; for example, after Hurricane Irma the state of Florida required LTCFs to have a generator, including enough fuel to run the generator for 96 h [99]. Larger hospital corporations can have disaster plans that provide additional generators to their facilities and electrical engineers to support installations just before major events [86]. Flashlights and portable generators are other alternative light/power sources [63], while batteries used to run ventilators (e.g. Ref. [59]).

Regarding alternative clean water supply, some facilities used bottled water (e.g. Refs. [44,63]) for immediate use. One study reported the availability of a "water contingency plan" where a supplier delivered water tanks [40], while another listed that facilities arranged bottled water delivery from local vendors, contracted trucking companies to deliver water from surrounding areas and purchased large tanks to store the purchased water [46]. Other preparedness/response measures include using water purifiers [40], temporarily installing reverse osmosis units to purify river water [44,46] and using local groundwater system [53]. Downey et al. [64] specified that among the seven hospitals included in their studies, none had (non-)potable water wells.

Considering the high financial loss HCFs suffer when flooded, they may need financial assistance from insurance and government agencies to prepare and recover better. Two studies explicitly mentioned that the facilities they studied were insured: (a) Ware [5] reported a hospital was fully insured, and (b) Siders and Jacobson [44] mentioned that a hospital purchased business interruption insurance for flood. Other studies implicitly mentioned that facilities received insurance reimbursement [35,74,82,83,90]. In the United States, the Federal Emergency Management Agency provides financial support for response, recovery and prevention [29,31,44,56,62,71,72,82,90].

4. Discussion

We identified that 77 % of the included studies were conducted in the United States. This result aligns with a systematic review that identified the United States as the most frequent study country for general health-related impacts of disasters caused by natural hazards [100]. Although Asian countries such as China, India, the Philippines and Indonesia are some of the most affected countries by floods [101], the number of studies about flood impacts on and preparedness of HCFs from those countries is quite low. To learn lessons from HCFs worldwide, more studies are needed. We also identified that hospitals are the most studied HCFs. More emphasis should also be given to other types of facilities, especially LTCFs, as they house several fragile people. McCann [19] emphasized that LTCFs and authorities should address the needs of the elderly during disasters.

Our review results show that evacuation is an important flood risk management strategy for HCFs. Two-thirds of the studies mentioned evacuation although the term “evacuation” was not specifically added to the search query. The findings also highlight the complex nature of evacuating HCFs, including the decision of whether to evacuate or not (which is related to evacuating before or after a flood event and evacuation orders), who to evacuate first, where to evacuate, which transportation means to use and how/when to return patients. Thus, the evacuation experience of facilities even within the same city and due to the same flood event can be different. Our findings are consistent with Khorram-Manesh et al. [13], which identified irregularity in evacuation practices among hospitals. The decision and preparedness to shelter in place also varies among HCFs. One solution to these irregularities could be the availability of regional or national standards and guidelines. For example, state-level guidelines for evacuation planning [102] and shelter in place [103] can comprehensively specify the principles and procedures for HCFs preparedness (see also [104]). It should be noted that relevant government agencies may assist evacuations (e.g., by providing transportation [29]), but evacuating facilities are usually responsible for contacting receiving facilities and coordinating the necessary arrangements. Hence, coordination with other HCFs (e.g., through healthcare coalitions [7]) is important to support and integrate their disaster risk management efforts, including evacuations. Furthermore, authorities could facilitate HCFs in case of mandatory evacuation orders by managing traffic and road congestion (e.g. diversifying routes for vehicles/ambulances).

Similar to the evacuation, our finding reveals major inconsistency in the contents and executions of disaster preparedness plans among HCFs. Richter [105] argued that facilities should not prepare plans only to comply with accreditation standards but to address properly their preparedness and survive when disasters occur. The plans should address several elements, including patient needs, evacuation procedures and disaster recovery, and facilities should organize disaster drills (including staff training) to accustom to the planned procedures. Facilities may also benefit from a more standardized approach towards disaster risk preparedness in general, with some elements of the standard contextualized for HCFs. For example, in the United States, all facilities that are accredited by The Joint Commission, which is an independent, not-for-profit organization, should follow emergency management standards (e.g., for hospitals [106] and nursing care centers [107]). These standards set the requirements and provide external references to more detailed toolkits (e.g. Ref. [23]). Moreover, the guidelines and standards should be periodically reviewed and reformed to incorporate deficiencies experienced in flood disasters [108]. Regarding implementation, HCF administrators should adhere to the plan as much as possible, especially if the plan is thorough and familiar to hospital staff. The availability of an adequate preparedness plan does not guarantee reduced impact if the plan is not utilized properly [85]. Nonetheless, some level of flexibility and improvisation to adapt to unforeseen circumstances is imperative [4].

Another finding of our review is that almost all the studies that reported power outages indicated that the HCFs had backup generators. However, several of those facilities reported that their generators did not function at all or long enough. One of the reasons was that generators, fuel pumps or switch boxes were flooded as they were placed in the basement or at the lower levels of facility buildings. As temporarily relocating generators is not an option during an emergency, they should be installed at higher levels or protected by water-tight doors [4]. Another reason for the malfunctioning of generators is a shortage of fuel [19], which should be addressed by adequate fuel storage at the facilities [99] and having a reliable supplier for emergencies [4]. As stated above, guidelines for authorities and facilities can improve HCFs resilience to power outages (e.g., Ref. [109]). Concerning alternative clean water sources, we found that HCFs follow different strategies. The findings conform with a review on the preparedness and response of HCFs to water supply emergencies [21]. They identified facilities used bottled water, storage tanks and groundwater wells. As in the case of fuel supplies, HCFs should prepare better by either contracting suppliers in advance or always storing water enough for some days instead of responding as a crisis unfolds. Facilities should consider digging wells, if there is the opportunity to pump out groundwater (e.g., Ref. [64]).

Permanent structural measures were not commonly reported as an implemented flood preparedness strategy in the studies we reviewed. The only HCFs that reported implementations of such measures were hospitals in Texas and Florida. These measures are costly and not all hospitals can afford to implement them. As noted by Hines and Reid [81], smaller hospitals in Texas had limited financial resources to install expensive and sophisticated flood risk reduction measures as in the case of the Texas Medical Center. In contrast to the studies we reviewed, a best practice document on HCFs resilience illustrated structural measures implemented by several facilities in the United States [110]. Internationally, HCFs could benefit from guidelines to assess structural and non-structural vulnerabilities, enabling them to devise renovation and retrofitting plans to strengthen their resilience to flood hazards (e.g. a World Health Organization's safe hospital guide [3]).

Although out of the scope of our flood-based analysis, cyclones also cause wind damage and HCFs must address such impacts. A few studies included in our review reported direct wind damage by tropical cyclones. Hurricane Juan blew away a hospital's roof, which led to leakage of rainwater on the 12th floor and below flooding operating and storage rooms [74]. The wind from Hurricane Hugo shattered the windows of a pediatric intensive care unit, requiring the relocation of patients to other intensive care units within the hospital [87]. Kleinpeter et al. [84] and Mitchell et al. [86] also stated roof damage to a dialysis center and a hospital, respectively, while Bernard and Mathews [78], Burger and Canton [79] and Chowdhury et al. [31] mentioned wind damages to hospital buildings. However, in a survey conducted to assess HCFs capacity after Hurricane Maria in Puerto Rico, Irvin-Barnwell et al. [28] quantified that 42 out of the 64 hospitals and 101 out of the 186 healthcare centers they assessed reported wind damage, including damage to windows and roofs. One way of preparing for wind impacts is by installing windows that can resist more than 200 km/h wind [36].

Our review has some limitations. Although the four databases we searched are reliable as principal search systems, the results may vary depending on institutional subscriptions, potentially leading to missing relevant studies [111]. Regarding the review process, half of the identified records (i.e., titles and abstracts) were screened by a single reviewer. Additionally, only one reviewer assessed the eligibility of full-text reports and extracted data from the included studies. This approach may have led to the omission of relevant studies and introduced potential error or bias in the results. Furthermore, our search was limited to scientific literature, and excluding gray literature may have affected the comprehensiveness of the analysis, especially in the reported risk management strategies. The decision to exclude non-English literature may have also contributed to the low number of studies from non-English speaking countries. Finally, we extracted data on patient deaths, injuries, and other relevant impacts only if reported in the included studies. The results about casualties (see Section 3.2.1) may be underestimated, as we did not include specific terms related to these impacts in our search query. For example, Jonkman et al. [112] reported that more than 220 bodies were recovered from hospitals and nursing homes due to the impact of Hurricane Katrina although their study did not mention the exact reasons for the deaths.

5. Conclusions

Given the critical role of healthcare facilities (HCFs) during disasters and the continuing impact of floods on these facilities worldwide, we conducted a systematic review to assess the consequences of floods on HCFs and the risk management measures they have implemented. One of the most significant impacts identified was basement flooding, which caused direct damage to HCF buildings, medical equipment, and other infrastructure. Interruptions to utilities, particularly power and water, also significantly affected healthcare services. While challenging in its implementation, patient evacuation was the most commonly reported measure among the HCFs analyzed in this review. Only few hospitals report implementation of permanent and temporary structural measures. Many HCFs had disaster preparedness plans in place, although there were inconsistencies in their content and implementation.

Based on the findings, we provide the following recommendations for future research and practice.

For research: Our review revealed that hospitals are the most widely studied HCF type. However, non-hospital facilities also play a critical role in providing services for outpatient care, the elderly, and others. A disruption to these facilities could place additional strain on hospital services during emergencies. As such, it is important to thoroughly examine the flood preparedness of non-hospital facilities to gather evidence and insights. Furthermore, our findings highlight the need for further research on the impacts and preparedness of HCFs in underrepresented and flood-prone regions, particularly in Asia, Africa, South America, and Europe. Generally, scenario-based analysis of flood impact and strategies could increase HCFs awareness and preparedness, as well as substantiate a preliminary overview of the effectiveness of adaptation options. Lastly, future reviews should incorporate gray literature to offer a more comprehensive understanding of flood impacts and HCFs preparedness.

For practice: The review emphasized that flood preparedness is a multifaceted process involving various factors. Consequently, the findings reveal inconsistencies in the flood preparedness of HCFs. Authorities should lead efforts in developing protocols and standards to assist HCFs in assessing potential flood impacts, alongside exploring available flood risk management measures. HCFs should receive guidance on standardizing and actively overseeing preparedness plans, including rehearsing and updating the plans. These exercises help ensure new staff and patients become familiar with the procedures. Additionally, local authorities should organize large-scale emergency drills and develop emergency plans to coordinate the preparedness efforts of multiple HCFs and other key responders, such as ambulances and police. Moreover, the availability of HCF building codes can help ensure the safe design, use and adaptation of these facilities. The codes should specify climate-resilient strategies, such as elevating building floors and placing backup generators and other essential equipment well above ground level. If basements are required, they should be designed to be flood-proof and reserved for non-essential purposes.

CRediT authorship contribution statement

Yared Abayneh Abebe: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Maria Pregnolato:** Writing – review & editing, Validation, Supervision, Project administration, Conceptualization. **Sebastiaan N. Jonkman:** Writing – review & editing, Supervision, Project administration, Funding acquisition,

Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Complete literature search strategy and results

The complete literature search queries for the four databases are given below. The resulting number of records is presented in Table A1.

Medline

(Floods/OR Cyclonic Storms/OR * Natural Disasters/OR (* Weather/AND * Disasters/) OR (flood* OR hurricane* OR cyclone* OR Typhoon* OR ((tropic* OR extreme*) ADJ3 storm*) OR superstorm* OR postkatrina OR postsandy OR postharvey OR postrita OR postandrew OR post-katrina OR post-sandy OR post-harvey OR post-rita OR post-andrew OR ((katrina OR sandy OR harvey OR rita OR andrew) AND (disaster* OR storm*)) OR ((disast* OR climate-chang* OR weather*) AND storm*)).ab,ti,kw. OR ((katrina OR sandy OR harvey OR rita OR andrew).ti. AND (disaster*).ab.)) AND (exp Health Facilities/OR Long-Term Care/OR Primary Health Care/OR Secondary Care/OR Tertiary Healthcare/OR Health Services/OR (((health* OR care* OR assisted-living OR medical*) ADJ3 (facilit* OR cent* OR organization* OR organisation*)) OR hospital* OR clinic* OR care-home* OR nursing-home* OR ((long-term* OR longterm* OR elder* OR geriatric*) ADJ3 (healthcare* OR care*)) OR eldercare* OR home*-for-the-aged OR pharmacy OR pharmacies OR Drug-store* OR ((Medical* OR Clinical*) ADJ3 laborator*)).ab,ti,kw. OR (healthcare OR health-care OR medical-care).ti.) AND (Risk Management/OR Health Policy/OR (prepar* OR planning* OR mitigat* OR (risk* ADJ3 management*) OR Recover* OR respons* OR adaptat* OR resilien* OR (policy ADJ3 recommend*)).ab,ti,kw.) AND english.la.

Embase

(flooding/de OR hurricane/de OR cyclone/de OR ’natural disaster’/mj OR (weather/mj AND disaster/mj) OR (flood* OR hurricane* OR cyclone* OR Typhoon* OR ((tropic* OR extreme*) NEAR/3 storm*) OR superstorm* OR postkatrina OR postsandy OR postharvey OR postrita OR postandrew OR post-katrina OR post-sandy OR post-harvey OR post-rita OR post-andrew OR ((katrina OR sandy OR harvey OR rita OR andrew) AND (disaster* OR storm*)) OR ((disast* OR climate-chang* OR weather*) AND storm*)):ab,ti,kw OR ((katrina OR sandy OR harvey OR rita OR andrew):ti AND (disaster*))) AND (’health care facility’/exp OR ’long term care’/de OR ’elderly care’/exp OR ’health care organization’/de OR ’medical care’/de OR ’primary health care’/exp OR ’secondary health care’/exp OR ’tertiary health care’/exp OR ’health service’/de OR (((health* OR care* OR assisted-living OR medical*) NEAR/3 (facilit* OR cent* OR organization* OR organisation*)) OR hospital* OR clinic* OR care-home* OR nursing-home* OR ((long-term* OR longterm* OR elder* OR geriatric*) NEAR/3 (healthcare* OR care*)) OR eldercare* OR home*-for-the-aged OR pharmacy OR pharmacies OR Drug-store* OR ((Medical* OR Clinical*) NEAR/3 laborator*)):ab,ti,kw OR (healthcare OR health-care OR medical-care):ti) AND (’risk management’/exp OR ’environmental resilience’/exp OR ’health care policy’/de OR ’disaster response’/exp OR (prepar* OR planning* OR mitigat* OR (risk* NEAR/3 management*) OR Recover* OR respons* OR adaptat* OR resilien* OR (policy NEAR/3 recommend*)):ab,ti,kw) NOT [conference abstract]/lim AND [english]/lim.

Web of Science

TS=((flood* OR hurricane* OR cyclone* OR Typhoon* OR ((tropic* OR extreme*) NEAR/2 storm*) OR superstorm* OR post-katrina OR postsandy OR postharvey OR postrita OR postandrew OR post-katrina OR post-sandy OR post-harvey OR post-rita OR post-andrew OR ((katrina OR sandy OR harvey OR rita OR andrew) AND (disaster* OR storm*)) OR ((disast* OR climate-chang* OR weather*) AND storm*))) AND (TS=(((health* OR care* OR assisted-living OR medical*) NEAR/2 (facilit* OR cent* OR organization* OR organisation*)) OR hospital* OR clinic* OR care-home* OR nursing-home* OR ((long-term* OR longterm* OR elder* OR geriatric*) NEAR/2 (healthcare* OR care*)) OR eldercare* OR home*-for-the-aged OR pharmacy OR pharmacies OR Drug-store* OR ((Medical* OR Clinical*) NEAR/2 laborator*)) OR TI=(healthcare OR health-care OR medical-care)) AND TS=((prepar* OR planning* OR mitigat* OR (risk* NEAR/2 management*) OR Recover* OR respons* OR adaptat* OR resilien* OR (policy NEAR/2 recommend*))) AND DT=(article) AND LA=(english)

Scopus

TITLE-ABS-KEY((flood* OR hurricane* OR cyclone* OR Typhoon* OR ((tropic* OR extreme*) W/2 storm*) OR superstorm* OR postkatrina OR postsandy OR postharvey OR postrita OR postandrew OR post-katrina OR post-sandy OR post-harvey OR post-rita OR post-andrew OR ((katrina OR sandy OR harvey OR rita OR andrew) AND (disaster* OR storm*)) OR ((disast* OR climate-chang* OR weather*) AND storm*))) AND (TITLE-ABS-KEY(((health* OR care* OR assisted-living OR medical*) W/2 (facilit* OR cent* OR organization* OR organisation*)) OR hospital* OR clinic* OR care-home* OR nursing-home* OR ((long-term* OR longterm* OR elder* OR geriatric*) W/2 (healthcare* OR care*)) OR eldercare* OR home*-for-the-aged OR pharmacy OR pharmacies OR Drug-store* OR ((Medical* OR Clinical*) W/2 laborator*)) OR TITLE(healthcare OR health-care OR medical-care)) AND TITLE-ABS-KEY ((prepar* OR planning* OR mitigat* OR (risk* W/2 management*) OR Recover* OR respons* OR adaptat* OR resilien* OR (policy W/2 recommend*))) AND DOCTYPE(ar) AND LANGUAGE(english)

Table A1
Databases searched using the above queries and the resulting number of records. No other database limits were used than those specified in the search strategies.

Database searched	Platform	Years of Coverage	Records
Medline ALL	Ovid	1946 - 20 November 2023	1469
Embase	Embase.com	1971 - 20 November 2023	2124
Web of Science Core Collection*	Web of Knowledge	1975 - 20 November 2023	1415
Scopus	Scopus.com	1823 - 20 November 2023	2492
Total			**7500**

*Science Citation Index Expanded (1975-present); Social Sciences Citation Index (1975-present); Arts & Humanities Citation Index (1975-present); Conference Proceedings Citation Index- Science (1990-present); Conference Proceedings Citation Index- Social Science & Humanities (1990-present); Emerging Sources Citation Index (2005-present).

Appendix B. Key characteristics of included studies

Table B1
A summary of the key characteristics of the included studies.

Study	Country	Hazard	HCF type	Impacts on HCFs					Flood risk management measures		
				Direct/indirect damage to HCF	Death or injuries	Utility interruptions			Disaster plan	Backup generator	Evacuated or Sheltered in place
						Power	Water	Telecom			
Degotardi and Grant [73]	Australia	Hurricane	Hospital	Flooded-Other	NR	Yes	Yes	NR	NR	NR	Evacuated-After
Little et al. [97]	Australia	Hurricane	Hospital	NR	No deaths	NR	NR	No	NR	Yes	Evacuated-Before
Woods et al. [93]	Australia	Hurricane	Hospital	NR	No deaths	NR	NR	NR	NR	NR	Evacuated-Before
Cloutier et al. [41]	Canada	Flood - Riverine	Hospital	NR	NR	NR	NR	NR	NR	NR	Evacuated-NS
Fulmore and Russell [74]	Canada	Hurricane	Hospital	Flooded-Other	NR	Yes	NR	NR	NR	Yes	Evacuated-After
Zhou et al. [51]	China	Flood - Pluvial	Hospital	Flooded-Basement	NR	Yes	NR	NR	NR	NR	Evacuated-After
Codjoe et al. [47]	Ghana	Flood - Riverine	Mixed facilities	Flooded-Other	NR	Yes	NR	NR	NR	Yes	NR
Kaliamoorthy et al. [50]	India	Flood - Pluvial	Hospital	Flooded-Other	No deaths	Yes	NR	NR	Yes	Yes	Evacuated-After
Inaba et al. [45]	Japan	Flood - Riverine	Hospital	Flooded-Other	No deaths	Yes	Yes	NR	NR	Yes	Evacuated-After
Khan et al. [55]	Pakistan	Flood - NS	Hospital	Flooded-Other	NR	Yes	Yes	NR	NR	NR	NR

(continued on next page)

Table B1 (*continued*)

Study	Country	Hazard	HCF type	Impacts on HCFs					Flood risk management measures		
				Direct/ indirect damage to HCF	Death or injuries	Utility interruptions			Disaster plan	Backup generator	Evacuated or Sheltered in place
						Power	Water	Telecom			
Irvin-Barnwell et al. [28]	Puerto Rico	Hurricane	Mixed facilities	Flooded-Other	NR	Yes	Yes	Yes	NR	Yes	NR
Simbawa [49]	Saudi Arabia	Flood - Pluvial	Hospital	Flooded-Basement	NR	Yes	NR	No	NR	Yes	NR
Lapcevic et al. [43]	Serbia	Flood - Riverine	PHC	Flooded-Basement	NR	NR	NR	Yes	NR	NR	NR
Farley et al. [54]	Sri Lanka	Flood - NS	Mixed facilities	Flooded-Other	NR	Yes	NR	Yes	NR	Yes	NR
Rattanakanlaya et al. [52]	Thailand	Flood - NS	Hospital	Flooded-Other	NR	NR	NR	NR	Yes	NR	NR
Rattanakanlaya et al. [53]	Thailand	Flood - NS	Hospital	NR	NR	NR	NR	NR	NR	Yes	NR
Adams [62]	US	Hurricane	Hospital	Flooded-Basement	No deaths	Yes	NR	Yes	NR	NR	Evacuated-Before
Apisarnthanarak et al. [75]	US	Hurricane	Hospital	Flooded-Other	NR	Yes	Yes	Yes	NR	Yes	Evacuated-Before
Arya et al. [76]	US	Hurricane	Pharmacy	Flooded-Other	NR	Yes	NR	NR	NR	Yes	NA
Azziz-Baumgartner et al. [91]	US	Hurricane	Pharmacy	NR	NR	Yes	NR	NR	NR	Yes	NA
Babar and Rinker [77]	US	Hurricane	Hospital	Flooded-Other	NR	Yes	NR	Yes	Yes	Yes	NR
Bernard and Mathews [78]	US	Hurricane	Hospital	Flooded-Other	Injuries	Yes	Yes	Yes	Yes	Yes	Evacuated-After
Berte and Narapareddy [39]	US	Flood - Riverine	Hospital	Flooded-Basement	NR	NR	NR	NR	NR	NR	Evacuated-After
Blanchard and Dosa [34]	US	Hurricane	LTCF	NR	Injuries	NR	NR	NR	NR	NR	Sheltered and Evacuated-Both
Brands et al. [36]	US	Hurricane	Hospital	NR	NR	NR	NR	NR	Yes	Yes	NR
Brevard et al. [63]	US	Hurricane	Hospital	Flooded-Basement	NR	Yes	Yes	Yes	Yes	Yes	Evacuated-NS
Brown et al. [37]	US	Hurricane	LTCF	NR	NR	Yes	NR	Yes	Yes	Yes	Sheltered and Evacuated-NS
Burger and Canton [79]	US	Hurricane	Hospital	Flooded-Other	NR	Yes	Yes	Yes	NR	Yes	Evacuated-After
Campese [80]	US	Hurricane	Hospital	Flooded-Other	No deaths	Yes	NR	No	Yes	Yes	Sheltered
Castro et al. [27]	US	Hurricane	LTCF	Flooded-Other	Deaths	NR	NR	NR	Yes	NR	Sheltered and Evacuated-NS
Chambers et al. [61]	US	Hurricane	Hospital	Flooded-Other	NR	No	NR	No	NR	NR	NR
Claver et al. [32]	US	Hurricane	LTCF	NR	Injuries	Yes	NR	NR	NR	NR	Sheltered and Evacuated-NS
Coolidge [48]	US	Flood - Riverine	Hospital	Flooded-Basement	NR	Yes	Yes	Yes	NR	NR	Evacuated-After
Dosa et al. [33]	US	Hurricane	LTCF	NR	NR	NR	NR	NR	Yes	Yes	Sheltered and Evacuated-Both
Downey et al. [64]	US	Hurricane	Hospital	Flooded-Basement	No deaths	Yes	Yes	NR	NR	Yes	Evacuated-Before
Duggal et al. [65]	US	Hurricane	Hospital	Flooded-Basement	No deaths	Yes	Yes	Yes	Yes	Yes	Evacuated-After

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Table B1 (*continued*)

Study	Country	Hazard	HCF type	Impacts on HCFs					Flood risk management measures		
				Direct/ indirect damage to HCF	Death or injuries	Utility interruptions			Disaster plan	Backup generator	Evacuated or Sheltered in place
						Power	Water	Telecom			
Espiritu et al. [29]	US	Hurricane	Hospital	Flooded-Basement	No deaths	Yes	NR	Yes	Yes	Yes	Evacuated-Both
Fang et al. [56]	US	Hurricane	Hospital	Flooded-Basement	NR	Yes	Yes	NR	Yes	Yes	Evacuated-After
Gallagher et al. [95]	US	Hurricane	Hospital	NR	No deaths	NR	NR	NR	Yes	NR	Evacuated-Before
Gray and Hebert [66]	US	Hurricane	Hospital	Flooded-Basement	Deaths	Yes	Yes	Yes	NR	Yes	Evacuated-After
Henkel and Marvanova [38]	US	Hurricane	Pharmacy	NR	NR	NR	NR	NR	Yes	Yes	NA
Hines and Reid [81]	US	Hurricane	Hospital	Flooded-Other	NR	NR	NR	NR	NR	NR	NR
Hutton and Allen [99]	US	Hurricane	LTCF	NR	NR	NR	NR	NR	Yes	NR	NR
Jarrett et al. [30]	US	Hurricane	Hospital	Flooded-Other	No deaths	NR	NR	NR	NR	NR	Sheltered and Evacuated-Before
Jiang and Tedeschi [82]	US	Hurricane	LTCF	Flooded-Other	NR	Yes	NR	Yes	NR	Yes	Sheltered and Evacuated-NS
Jiang et al. [83]	US	Hurricane	LTCF	Flooded-Other	No deaths	Yes	Yes	Yes	Yes	Yes	Sheltered and Evacuated-NS
Kleinpeter et al. [84]	US	Hurricane	Dialysis center	Flooded-Other	NR	NR	NR	Yes	NR	NR	NA
Levinson [67]	US	Hurricane	Hospital	Flooded-Basement	No deaths	Yes	Yes	Yes	NR	Yes	Sheltered and Evacuated-Both
McCaughrin and Mattammal [60]	US	Hurricane	Hospital	Flooded-Other	No deaths	Yes	Yes	Yes	NR	Yes	Evacuated-After
McGinty et al. [68]	US	Hurricane	Hospital	Flooded-Basement	NR	Yes	Yes	NR	Yes	Yes	Sheltered and Evacuated-Both
McGlown and Fottler [85]	US	Hurricane	Hospital	Flooded-Other	NR	Yes	Yes	NR	NR	NR	Evacuated-NS
Mitchell et al. [86]	US	Hurricane	Hospital	Flooded-Other	NR	Yes	Yes	Yes	NR	Yes	NR
Nates [59]	US	Hurricane	Hospital	Flooded-Basement	NR	Yes	Yes	Yes	NR	Yes	Evacuated-After
Norcross et al. [87]	US	Hurricane	Hospital	Flooded-Other	No deaths	Yes	Yes	No	NR	Yes	Sheltered
Ofri [69]	US	Hurricane	Hospital	Flooded-Basement	NR	Yes	Yes	NR	Yes	Yes	Evacuated-After
Peters [46]	US	Flood - Riverine	Hospital	NR	NR	Yes	Yes	Yes	NR	Yes	NR
Peterson et al. [98]	US	Hurricane	LTCF	NR	NR	NR	NR	NR	Yes	NR	Sheltered and Evacuated-NS
Peterson et al. [92]	US	Hurricane	LTCF	NR	NR	Yes	NR	NR	Yes	Yes	Sheltered and Evacuated-NS
Ramme et al. [70]	US	Hurricane	Hospital	Flooded-Basement	NR	Yes	Yes	NR	NR	Yes	Evacuated-After
Ramsey [40]	US	Flood - Riverine	Hospital	NR	No deaths	Yes	Yes	Yes	Yes	Yes	Sheltered

(*continued on next page*)

Table B1 (*continued*)

Study	Country	Hazard	HCF type	Impacts on HCFs					Flood risk management measures		
				Direct/ indirect damage to HCF	Death or injuries	Utility interruptions			Disaster plan	Backup generator	Evacuated or Sheltered in place
						Power	Water	Telecom			
Reed [42]	US	Flood - Riverine	Hospital	Flooded-Basement	NR	NR	Yes	NR	Yes	Yes	Evacuated-After
Scott and Hutchison [88]	US	Hurricane	Hospital	Flooded-Other	NR	NR	NR	NR	NR	NR	Evacuated-Before
Seale [35]	US	Hurricane	PRF	Flooded-Other	NR	NR	NR	NR	Yes	NR	Evacuated-Before
Sexton et al. [94]	US	Hurricane	Hospital	NR	NR	NR	NR	NR	Yes	NR	Evacuated-Before
Siders and Jacobson [44]	US	Flood - Riverine	Hospital	Flooded-Other	NR	NR	Yes	NR	NR	NR	Evacuated-After
Sirbaugh et al. [58]	US	Hurricane	Hospital	Flooded-Other	NR	Yes	NR	NR	NR	Yes	Evacuated-After
Son et al. [71]	US	Hurricane	Hospital	Flooded-Basement	NR	Yes	NR	No	NR	Yes	NR
Stall [89]	US	Hurricane	LTCF	Flooded-Other	Deaths	NR	NR	NR	Yes	Yes	Sheltered
Stephens et al. [57]	US	Hurricane	Hospital	Flooded-Basement	NR	NR	NR	NR	NR	NR	NR
Taylor [72]	US	Hurricane	Hospital	Flooded-Basement	Deaths	Yes	NR	NR	NR	Yes	Evacuated-After
Thomas and Lackey [96]	US	Hurricane	Hospital	NR	No deaths	NR	NR	NR	Yes	Yes	Evacuated-Before
Verni [90]	US	Hurricane	Hospital	Flooded-Other	No deaths	NR	NR	NR	Yes	NR	Evacuated-Before
Ware [5]	US	Flood - Riverine	Hospital	Flooded-Basement	NR	Yes	NR	NR	NR	Yes	Evacuated-After
Chowdhury et al. [31]	US Virgin Islands	Hurricane	Hospital	Flooded-Other	NR	Yes	NR	NR	NR	NR	Evacuated-After

US = United States, HCF = Healthcare facility, LTCF = Long-term care facility, PRF = Postacute rehabilitation facility, PHC = primary health center, NS = Not specified, NR = Not reported, Telecom = Telecommunication services, NA = Not applicable, Sheltered = Sheltered in place.
Flooded-basement = This is commonly related to direct damage to one or more of the following HCF functions: a pharmacy, laboratory, information services, data center, supplies and distribution center, morgue, backup generators and elevator systems.
Flooded-other = For brevity, all other direct and indirect impacts such as above-ground floods causing structural and equipment damages, flooded access roads obstructing patients and supplies delivery, and reported financial losses are included in this category.
Disaster plans are also called emergency or preparedness plans.
Evacuated-Both = This refers to studies that reported evacuations of different HCFs before and after the flood started.
Evacuated-NS = This refers to studies that did not specify when the evacuation occurred.
Some studies reported both evacuations and shelter in places of different HCFs.

Data availability

The research data (i.e., non-duplicate records, the reports sought for retrieval, and the list and characteristics of the included studies) are available at the 4TU.ResearchData repository and are openly accessible at https://data.4tu.nl/datasets/1795829c-d2bb-415d-aa5f-03f02e73ff04.

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