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A modelling framework to design an evacuation support system for healthcare infrastructures in response to major flood events

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ABSTRACT

Extreme weather events such as floods are predicted to become increasingly common and severe as the climate changes. Effectively functioning hospitals are critical to a community's resilience to the adverse health impacts of such events. Yet many hospitals have not been designed with extreme weather risks in mind and are built in flood-prone areas, raising concerns about their ability to support community healthcare needs when they eventuate. While considerable research has been conducted on developing disaster responses to maintain healthcare services in the face of floods, there is a paucity of research on hospital evacuating planning. Addressing this critical gap in research, this paper explores current state-of-the-art hospital evacuation transportation models to identify key factors for developing more effective evacuation planning for future flooding risks. A new modelling framework is proposed, which addresses the limitations of existing hospital evacuation models and proposes factors that should be incorporated into future models to enhance community resilience to growing flood risks due to climate change.

1. Introduction

Many countries are experiencing the impacts of global climate change, particularly the increased frequency and magnitude of extreme weather events (EWEs) such as storms, heatwaves and floods [1]. Both developing and developed countries are vulnerable to the devastating impact of floods [2]. Floods severely interrupt the normal functioning of society [3] and many urban areas across the world have been developed in highly flood-prone areas [4]. For instance, in Australia, over 80% of the population lives in coastal regions, with a large proportion of these areas prone to flooding [5]. Many Australian hospitals are also exposed to flood risks since they have been built in floodplains and near rivers where cheap and flat land was available [3]. Many have also been designed without consideration of future climate change risks [6].

Hospitals play a significant role in supporting a disaster-resilient society, and it is critically important that they remain functional, particularly in disasters [7]. However, there is strong evidence in many countries hospitals have been unable to provide reliable services during such events. In such cases, evacuating at-risk patients to hospitals in safer locations may be the most reasonable and effective response action [3]. Indeed, climate change-induced extreme weather events (EWEs) are the most common cause for hospital evacuation [9], and among them, floods are the most frequently occurring type of natural hazard. For example, in January 2013, heavy flooding hit southern Queensland, causing major flooding and damage to a number of hospitals in the area which required a number of hospitals to be evacuated [10]. When Hurricane Katrina hit New Orleans, Louisiana, ten of the city's major hospitals decided not to evacuate, resulting in dozens of deaths[11]. When Hurricane Rita hit Louisiana and Texas, 23 patients on a bus evacuated from a hospital died because of a poor planning[12]. In another incident, 34 patients of a nursing facility in Chalmette, Louisiana drowned when the administration chose to shelter-in-place [13]. Hurricane Harvey, which made landfall on the Texas coast in August 2017, flooded at least 25% of Harris County causing damage to numerous hospitals and resulting in patient evacuations despite many roads being flooded[14]. Other research shows that many hospitals experience serious problems in transferring patients and resources to other safe locations [15].

Hospital evacuations are complicated by a floods' unpredictable behaviour and the difficulties associated with patients as evacuees [3]. Patients require assistance and medical care during the evacuation process, and hospitals and access roads may be flooded, complicating the evacuation response. In these circumstances, effective transportation planning is critical. While there are many studies in healthcare planning in normal situations [16–20], very little research has been conducted into hospital

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evacuation planning [3]. In addition, past studies have been limited to relief goods distribution problems [21–24] and the problem of where and how each patient should be transported to mitigate risk to patient safety is a critical question which is typically determined in practise through manual evacuation drills. However, evacuation drills are ineffective and difficult to evaluate in practise [25]. Additionally, they are prohibitively expensive and do not allow for the evaluation of all possible scenarios. As a result, decision-makers may encounter unexpected situations during a hospital evacuation, which when combined with the limited time available to make a decision, can create potentially life-threatening risks for patients. Surprisingly, while science and technological advancements present significant opportunities for developing more effective decision support methods, they remain unexplored in the context of hospital evacuation planning [25].

The aim of this paper is to address this important gap in research by exploring current state-of-the-art hospital evacuation transportation models to identify key factors for developing more effective evacuation planning for future flooding risks. A new modelling framework is proposed, which addresses existing model limitations and proposes factors that should be incorporated into future hospital evacuation models to support decision-makers in coping with the evacuation planning challenges faced by hospitals once floods occur. Such a framework is critical to make healthcare infrastructure and dependent communities more resilient to floods and in addressing a critical gap in existing hospital evacuation planning research. As a report by World Health Organization (WHO) states, [26] "*there has been little research on the impact of flooding on health facilities*," despite hospitals being vulnerable to flooding risks in many other countries around the world [27]. For example, in the United Kingdom, 70% of hospitals are situated in flood zones [28]. Furthermore, in Thailand's 2011 floods, 561 hospitals were severely affected, resulting in a reduction in healthcare services to the community [29].

2. Evacuation planning perspective in hospital disaster risk management

2.1. Disaster risk management for hospitals

Disaster risk management (DRM) refers to the processes of developing, implementing and evaluating strategies, policies and measures to improve our understanding of disaster risk, promote disaster risk reduction and transfer and encourage continuous improvement in disaster mitigation, preparedness, response and recovery [30][31]. [32]. The disaster risk management process is generally regarded as part of a continuous and interrelated process, including mitigation, preparedness, response and recovery, [32] Similarly, the American Society for Healthcare Risk Management (ASHRM) defines emergency management in healthcare institutions as a four-step process of prevention, planning and preparation, implementation, reaction, and recovery [33]. The preventative activities focuses on developing powerful internal reporting systems to detect early indicators of impending disasters. Emergency managers ensure that suitable emergency plans are established and maintained efficiently throughout the planning and preparedness stages. The implementation and response phase involves the deployment of emergency plans and the provision of the first response to incidents. The last stage of recovery entails financial, operational, and psychological efforts to restore pre-crisis circumstances.

As discussed earlier, recent disasters have highlighted the need for a more comprehensive approach for healthcare disaster management planning [7]. In particular, there is a need for more effective evacuation planning [3]. Therefore, hospitals and other health care facilities need to check their evacuation policies and plans to make sure they can deal with the extra challenges that come with extreme weather, such as major floods.

2.2. Hospital evacuation planning

Generally, "evacuation" is defined by the United Nations International Strategy for Disaster Reduction (UNISDR) as "*Moving people and assets temporarily to safer places before, during or after the occurrence of a hazardous event in order to protect them*" [34]. Evacuation planning is an important part of the disaster management cycle [3] and The United Nations International Strategy for Disaster Reduction (UNISDR) defines an evacuation plan as "*the arrangements established in advance to enable the moving of people and assets temporarily to safer places before, during or after the occurrence of a hazardous event. Evacuation plans may include plans for return of evacuees and options to shelter in place*" [34].

Having an efficient evacuation plan is one of the most important steps in emergency hospital management [35] and effective plans have both internal and external elements. Internal (partial) hospital evacuation refers to the evacuation of part of a hospital which is damaged [36]. External (complete) evacuation is the evacuation of patients to pre-determined acceptable hospitals when the hospital has been destroyed and is no longer useful or when the danger to the hospital is present [36]. While internal evacuation has been extensively studied in recent years [37], external evacuation remains relatively un-researched and is the focus of this paper. While there are many aspects of this problem to explore, Yazdani, Mojtahedi, Loosemore, Sanderson and Dixit [3] asserted that due to the difficulties of transporting patients, staff, and equipment to other hospitals via the transportation network, this is the most ignored step of a hospital evacuation. Addressing the lack of research in this area is important because, in recent years, many countries have experienced major hospital evacuations in response to a wide range of disasters, including major floods [38].

2.3. Transportation planning in hospital evacuation process

Evacuation planning and management is a complex activity with numerous interdependent components that are performed in time-critical conditions. The Department of Health and Environmental Control (DHEC) in the US has issued an order mandating all hospitals establish an evacuation plan that includes the following elements: shelter, transportation and personnel [39]. Agca [40] states every hospital must have evacuation plans to ensure the safety of patients in an emergency, but there is no standard plan that can respond to all possible emergencies successfully.

A review of the literature shows that hospital evacuation has five steps. The procedure begins with the detection of an incident. In the next step, a decision is made according to the situation. Whether preparing for a predicted disaster or dealing with an actual emergency, decision-makers must weigh the uncertainties, risks, costs and the window for evacuations [41]. Patients are prepared for evacuation in the next step, step III. It is critical for patients to have relevant medical documents and medicines while preparing them for evacuation. After patients have been readied for transfer and triaged, it is critical to convey them through the hospital to the staging area quickly and safely. Step IV of planning the transfer of patients, personnel and equipment to other hospitals through a transportation network is difficult and one of the most ignored components of an evacuation. Poor resource planning and scheduling, especially for scarce vehicles such as ambulances, has been recognised as one of the most common concerns in hospital evacuation [9]. When the triggering incident has been handled, the last step is to return to the hospital. The fourth step is the focus of this study (Fig. 1).

2.4. Role of modelling in effective evacuation planning

Planning to transfer patients, personnel and equipment to other hospitals through a transportation network that is at risk of being flooded is complex. Most hospitals usually have severe difficulties transferring patients and resources to other healthcare facilities [3]. Poor resource planning and scheduling, particularly for scarce vehicles such as ambulances, is a challenge for hospital evacuation. Failing to allocate and schedule ambulances on time may exacerbate the crisis situation and increase the number of casualties during a hospital evacuation. Prior experiences demonstrate that decision-makers often fail to take quick action while evacuating a hospital, significantly increasing the casualties.

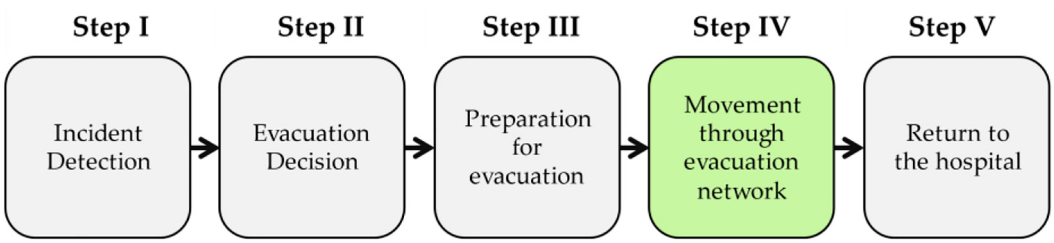

Fig. 1. Evacuation phases adopted from Yazdani, Mojtahedi, Loosemore, Sanderson and Dixit [3].

Due to the complications inherent in hospital evacuation planning, it is becoming more vital to develop creative, rapid and accurate decision-making approaches for dealing with emergency situations. The development and use of innovative models and approaches to aid decision-making in healthcare has accelerated, and a number of approaches, including mathematical modelling, have been used.

Neumaier [42] defines *mathematical modelling* as "the *art of translating problems from an application area into tractable mathematical formulations whose theoretical and numerical analysis provides insight, answers, and guidance useful for the originating application*." Modelling approaches can effectively condense our understanding of real-world decision-making problems and highlight their most important aspects. Then, this model can be solved using mathematical tools. The obtained solutions are then interpreted into real terms. The mathematical modelling process is illustrated in Fig. 2.

As illustrated in Fig. 2, the modelling process begins with the consideration of a real-world problem, and the goal is to find a solution for this real case. Variables, constraints and assumptions are identified, and relationships between variables are defined during the modelling stage. The most difficult stage of this process is model formulation. Following the development of the model, the next stage is to identify an appropriate technique for solving the model. The model's output is then interpreted in the context of the real-world problem, and the solutions are compared to the collected data.

Although mathematical modelling methods are promising to address a wide range of difficult decision-making problems, the available models in hospital evacuation planning can only be considered as first steps towards a more profound understanding of hospital evacuation planning, as many questions regarding formulation remain to be addressed [3]. Therefore, in the following sections, the main factors that should be incorporated in the mathematical modelling are extracted from the literature and a framework is proposed to assist model developers to develop a comprehensive hospital evacuation plan.

3. Hospital evacuation planning: Factors required for modelling, gaps, and future insights

3.1. Factors that affect evacuation models

When the UNISDR definition of evacuation is applied to hospitals in an extreme flood, it can be redefined as *"Moving* ***patients*** *from* ***under risk hospitals*** *to safer* ***places*** *before, during or after the occurrence of a* ***hazardous event*** *to protect them using* ***available resources****.*" Some factors are defined based on these key words:

1) **Number of patients and their classification:** Prior to beginning a hospital evacuation, decision-makers should determine the order in which patients should be evacuated. As a result, "triage" may assist in determining the optimal patient prioritising. According to Gray and Hebert [11] an agreement must be made prior to the evacuation of patients. It is rational to make decisions based on the current circumstances since there is no one priority strategy that works equally well for all hospitals and all situations [44]. The number of patients and their readiness for evacuation are critical concerns. The number of patients is not known with certainty during the evacuation for a variety of reasons. When a hospital evacuation is ordered, the number of patients in the hospital is swiftly reduced by as many early discharges as feasible [45], hence the overall number of patients to be evacuated is sometimes less than the total patient census. For instance, The number of patients at Memorial Hermann Hospital and Memorial Hermann Children's Hospital in Texas were reduced from 575 to 406 during Tropical Storm Allison in 2001 [44].
2) **Available staff assignment and scheduling:** During hospital evacuations, staff shortages are a major concern [46]. Depending on the type of disaster, staff shortages are likely to arise. During a disaster, staff numbers may be drastically reduced. For example, during the 1979

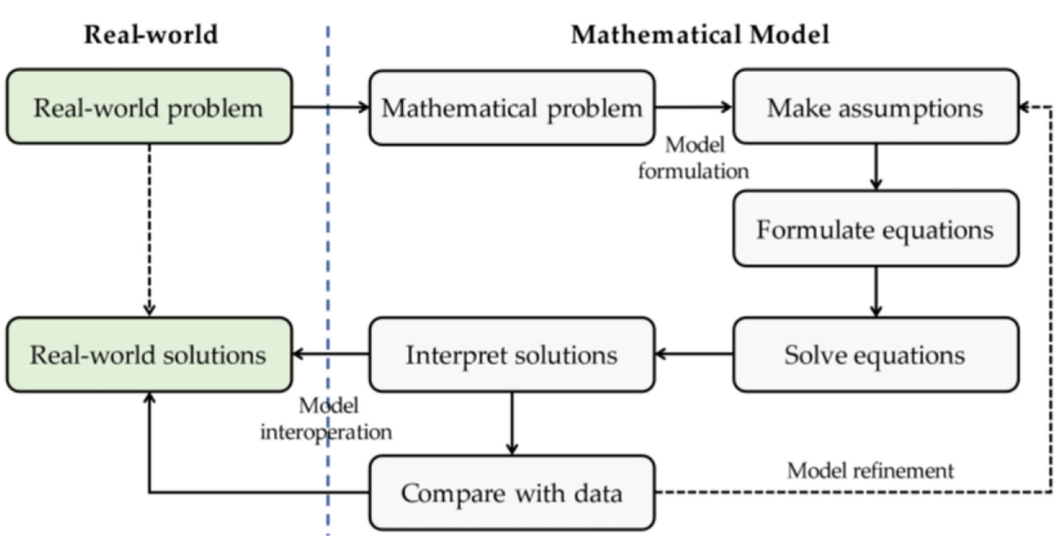

Fig. 2. The modelling process adopted from [43].

Three Mile Island nuclear power plant disaster, many medical personnel abandoned the area to protect their families, resulting in a significant staffing shortage in multiple hospitals [47]. In a hospital evacuation, certain hospitals may have personnel on standby or may depend on volunteers. In 2011, Memorial Hermann Hospital was evacuated with the help of a huge number of volunteers [48]. Consequently, the hospital evacuation plan must include the number and availability of personnel.

3) **Available transportation resources:** While in most evacuation circumstances, evacuees are expected to be able to go to safe locations in their own cars, many patients in hospital evacuations need ambulances or special vehicles for transportation. Transportation resources, particularly ambulances and their availability, have been identified as a challenge in a hospital evacuation [49]. Vehicles other than ambulances, such as public buses, may be used to transport patients [50]. Buses are generally available in cities and can transport people in wheelchairs [51]. If the availability of transportation resources or routes is affected as a result of the disaster, alternative modes of substitute transportation may be necessary [48]. When Tropical Cyclone Yasi made landfall in northern Queensland in February 2011, all patients unable to be released from the two hospitals (one public and one private) in Cairns were airlifted to Brisbane, roughly 1700 km away [52]. In certain situations, boats may be required to transport patients. After Hurricane Katrina patients were transferred by boat from Charity Hospital in Louisiana to locations where land transportation or a helicopter was available [11]. When the number of patients exceeds the number of ambulances, other modes of transportation may be considered. McGovern and Bogucki [53] described the conventional and non-medical vehicles used in patient evacuation.
4) **Evacuating and receiving hospitals and their capacities:** The number of patients that a receiving hospital may accept during an evacuation is determined by its capacity and occupancy rate. While a hospital may have a plan to move patients to specified receiving hospitals, these facilities themselves may have been forced to evacuate or may have already been occupied by patients from other regions and the planned receiving hospitals may not be accessible [54]. Moreover, some hospitals may be unable to accept patients with particular conditions due to a lack of staff or resources [54]. In an emergency situation detailed in [55], the receiving hospital's capacity was more than the number of patients, and so the receiving hospital admitted all of the evacuated patients. However, in many emergency cases, transporting patients to various hospitals may help minimise overcrowding at a single facility [48]. In a real-world scenario, the capacity of other hospitals may be reduced in emergency circumstances, and some may even be evacuated. Certain hospitals may be unable to accept certain types of patients. The distance from the receiving hospital is a significant element in reducing the time required for the evacuation operation. Many alternative hospitals may be similarly vulnerable to natural disasters. As a result, defining the ideal number, location and capacity of receiving hospitals in terms of optimal number, location and capacity is vital in hospital evacuation planning.
5) **Road network and traffic conditions:** For a rapid and effective evacuation system, the road network is important [56]. It is commonly assumed in research that these systems are running at or near their design capacity, but the road network may be in danger in a disaster such as a flood. An area's road network may be compromised when a disaster occurs. Patients' lives are at risk if the transportation network is unreliable, hence performance indicators for the network are important in planning an evacuation. Emergency scenarios may cause a breakdown in the network's ability to evacuate people [56], and not all roads in a network may be accessible at all times as a widespread disaster may affect many portions of a route at the same time. There is a separate time frame in which each portion of the road may be evacuated. If one road section is flooded, all roads connected to it will be inaccessible. Evacuation efficiency depends on the route chosen, and emergency planners may benefit from a greater knowledge of the reliability of the evacuation network [56]. Despite the evacuation environment facing a broad range of threats, little emphasis has been given to integrating road network performance measurements into hospital evacuation models.
6) **Disaster behaviour analysis:** The nature of a disaster may have a significant influence on the proposed approach for hospital evacuation. To effectively simulate hospital evacuation, two variables must be considered: the nature of the event, including its impacting time, predictability, magnitude and impact zone, and the projected impacts. In hospital evacuation planning, disasters may be "Advanced Warning Events" or "No Advanced Warning Events" [57]. In the case of impending disasters such as floods, decision-makers have time prior to the event for evacuation, whereas in No Advanced Warning Events such as earthquakes, evacuation occurs either during or immediately after the disaster. Although the physical impacts of disasters vary greatly among disaster types, hospital evacuation strategy has not been thoroughly addressed in previous literature.
7) **Evacuation modelling objectives:** Many different types of objectives may be considered depending on the nature, time frame and intensity of the disaster, as well as the goal of the emergency decision-makers. In general, hospital evacuation planning objectives fall into three categories: time-dependent objectives, cost-dependent objectives, and risk-dependent objectives. Certain goals from urban evacuation planning studies can also be incorporated including limiting the overall evacuation time, minimising the maximum latency, minimising the clearance time, increasing the number of patients who reach safety before a defined critical time T, and minimising the average evacuation time [58]. In the context of a hospital evacuation, maximum latency can be defined as the sum of the total trip times incurred by the vehicles. Latency is defined as the total amount of time it takes a vehicle to complete a journey on a specific route, and clearing time is defined as the moment the last vehicle in the network leaves the danger zone and arrives at a safe location.

3.2. Current studies in transportation hospital evacuation modelling

Despite substantial research assessing previous experiences in which natural disasters have influenced hospital healthcare delivery, there is a shortage of modelling research in the literature addressing transportation during hospital evacuation. Taaffe, Johnson and Steinmann [59] used simulation to assess how long it would take to transfer patients from a hospital to other healthcare facilities. To minimise operational and evacuation costs, Tayfur and Taaffe [41] suggested a mixed integer programming framework for determining resource scheduling and allocation. As time passed, the model calculated how many patients of each kind should be transported to different hospitals in various vehicles and how many vehicles and nurses were available for staging and transfer. S-shaped curves and triangular distributions, as well as a heuristic solution, were used by Tayfur and Taaffe [39] to illustrate stochastic vehicle travel and waiting times, as well as the number of vehicles and nurses necessary to evacuate patients at the lowest feasible cost. It was also determined whether the commencement time of the evacuation affected the cost and duration of the operation. Optimising how patients are distributed across multiple receiving hospitals was studied by Bish, Agca and Glick [60]. Capacity of receiving hospitals, types of patients, and vehicle limitations were all taken into consideration during planning. Chen, Guinet and Ruiz [61] developed a simulation model that incorporates both internal and external resources like stretchers and ambulances. As part of this research, a factorial experimental design was used to test essential components' influence on evacuation time. Rabbani, Zhalechian and Farshbaf-Geranmayeh [62] introduced a bi-objective mathematical model for hospital evacuation that minimised both the overall weighted number of patients who were not evacuated and the total evacuation time. To deal with the unknown character of the parameters, possibilistic programming was used, and two metaheuristic algorithms were used to solve the problem. Kim, Kutanoglu, Hasenbein, Wu and Yang [63] developed a two-stage stochastic mixed-integer programming system. In the first step, the model identifies the location of staging sites and the number of vehicles, and in the second stage, vehicle route assignments are assigned, all while minimising the anticipated total cost of patient evacuation operations. Rambha, Nozick, Davidson, Yi and Yang [64] used a multi-stage stochastic algorithm to find the optimum number of various sorts of patients who must be evacuated at different times to receiving hospitals, as well as the vehicles used to carry them. The objective of the study was to minimise a linear combination of risk and expense associated with evacuation. Factors which were discussed in Section 3.1 are extracted from the literature and presented in Table 1.

4. The framework for developing hospital evacuation transportation planning

The evacuation process is a complicated phenomenon. It comprises the interactions between patients and evacuation coordinators, hazardous situations and environment settings. A complete modelling framework consisting of three broad levels of decision-making is used to arrange the hospital evacuation modelling research, as indicated in Fig. 3.

Table 1
Factors used in developing hospital evacuation modelling.

The main group	Factors	Taaffe, Johnson and Steinmann [59]	Tayfur and Taaffe [41]	Tayfur and Taaffe [39]	Bish, Agca and Glick [60]	Chen, Guinet and Ruiz [61]	Rabbani, Zhalechian and Farshbaf-Geranmayeh [62]	Kim, Kutanoglu, Hasenbein, Wu and Yang [63]	Rambha, Nozick, Davidson, Yi and Yang [64]
Number of patients and their classification	Number of patient categories	Several groups of patients	Several groups of patients	Several groups of patients	Several groups of patients	Only one group of patients	Several groups of patients	Several groups of patients	Several groups of patients
	Priority of patient categories	No priority	No priority	Critical patients have highest priority	No priority	No priority	Critical patients have highest priority	No priority.	No priority
	Number of patients	Static & deterministic*	Static & deterministic	Static & deterministic	Static & deterministic	Static & deterministic	Static & stochastic	Static & stochastic	Static & deterministic
	Ready time of patients for evacuation	Before starting the evacuation	Before starting the evacuation	Not before starting the evacuation	Before starting the evacuation	Not before starting the evacuation	Before starting the evacuation	Before starting the evacuation	Before starting the evacuation
Available staff assignment and scheduling	Number of staff groups	Several groups	Several groups	Several groups	–	Several groups	–	–	–
	Number of staff	Static & deterministic	Decision variable in the model	Decision variable in the model	–	Decision variable in the model*	–	–	–
	Ready time of staff	Before starting the evacuation	Before starting the evacuation	Before starting the evacuation	–	Before starting the evacuation	–	–	–
Available transportation resources	Number of land vehicle groups	Several groups of vehicles	Several groups of vehicles	Several groups of vehicles	Several groups of vehicles	Only one group of vehicles	Several groups of vehicles	Several groups of vehicles	Several groups of vehicles
	Number of vehicles	Static & deterministic	Decision variable in the model	Decision variable in the model	Static & deterministic (in the different periods, there are different numbers of vehicles)	Decision variable in the model*	Static & stochastic (in different periods, there are different numbers of vehicles)	Decision variable in the model**	Static & deterministic
	Availability of vehicles	Before starting the evacuation	Before starting the evacuation	Before starting the evacuation	Time-dependent	Before starting the evacuation	Time-dependent & stochastic	Before starting the evacuation	Before starting the evacuation
	Except land vehicles	–	–	–	–	–	Helicopter	–	–
Evacuating and receiving hospitals and their capacities	Number of evacuating hospitals	One hospital	One hospital	One hospital	One hospital	One hospital	Several hospitals	Several hospitals	One hospital
	Number of receiving hospitals	Several hospitals	Several hospitals	Several hospitals	Several hospitals	One hospital	Several hospitals	Several hospitals	Several hospitals
	Capacities of receiving hospital(s)	Deterministic, but can be expanded	Static & deterministic	Static & deterministic	Static & deterministic	Have enough space to accommodate all patients	Static & deterministic	Static & deterministic	Static & deterministic
Disaster behaviour analysis	Disaster in the model	–	–	–	–	–	–	Yes	Yes
Road network and traffic conditions	Time of evacuation	Prior to the disaster	Prior to the disaster	Prior to the disaster	Prior to the disaster	Prior to the disaster	During the disaster	Prior to the disaster	Prior to & during the disaster
	Evacuation planning horizon	Not limited	Limited & fixed	Limited & fixed	Limited & fixed	Limited & fixed	Limited & fixed	Limited & fixed	Limited & fixed

(continued on next page)

Table 1 (*continued*)

The main group	Factors	Taaffe, Johnson and Steinmann [59]	Tayfur and Taaffe [41]	Tayfur and Taaffe [39]	Bish, Agca and Glick [60]	Chen, Guinet and Ruiz [61]	Rabbani, Zhalechian and Farshbaf-Geranmayeh [62]	Kim, Kutanoglu, Hasenbein, Wu and Yang [63]	Rambha, Nozick, Davidson, Yi and Yang [64]
	Impact of disaster on the routes	–	–	–	–	–	Known before evacuation	–	Risk due to flooding of highway links
	Travel time	Stochastic & subject to change over time due to traffic congestion	Static & deterministic	Depending on traffic congestion, it may change over time	Static & deterministic	Stochastic	Stochastic	Static & deterministic	Changes are possible at any time for different departure times
Evacuation modelling objectives	Modelling approach	Simulation model	Mathematical model	Simulation model*	Mathematical model	Simulation model	Mathematical model	Mathematical model	Mathematical model
	Objective	Single	Single	Single	Single		Bi-objective	Single	Bi-objective
	Model objective	Time related	Cost related	Cost related	Risk related	Time related	Time related & number of evacuated patients	Cost related	Cost & risk related

4.1. Incorporating flood simulation and its impacts in hospital evacuation modelling

Modelling flood conditions and the effect of flooding on built environments is shown in the top row of Fig. 3 and serves to analyse the flood and its associated challenges. Evacuation studies may use some computational models such as the hydro-inundation model to analyse the behaviour of the flood. The first level of the proposed framework simulates the behaviour of the flood in the evacuation area to help decision-makers understand the potential impacts of the flood on the road network in different time horizons and possible impacts on the built environment. The flood simulator should be able to predict the dynamic behaviour of the flood. The time of availability of each road in the network can be estimated by a flood simulator. The outputs of this step are used to find the shortest path between different hospitals in different time periods. The first step of this level starts with flood modelling. To ensure sufficient detail in terms of the depth and extent of a flood event, fine-scale modelling of a flood and its impacts on the built environment requires the use of a numerical tool capable of large-scale flood modelling. Flood inundation modelling is a very rich and broad research area. Teng, Jakeman, Vaze, Croke, Dutta and Kim [65] reviewed state-of-the-art empirical, hydrodynamic and simple conceptual models for determining flood inundation. There are two kinds of hydrodynamic modelling techniques: empirical approaches, such as measurements, surveys and remote sensing, and statistical models which evolved from these data-based methods [65]. Hydrodynamic models, which include one-dimensional (1D), two-dimensional (2D) and three-dimensional (3D) methodologies, can imitate water flow by solving equations obtained from applying scientific rules to fluid motion of various complexity [65]. Teng, Jakeman, Vaze, Croke, Dutta and Kim [65] listed some typical hydrodynamic models and their developers (Table 2).

After flood simulation, some approaches are needed to evaluate the impact of the disaster on the built environment particularly the road network.

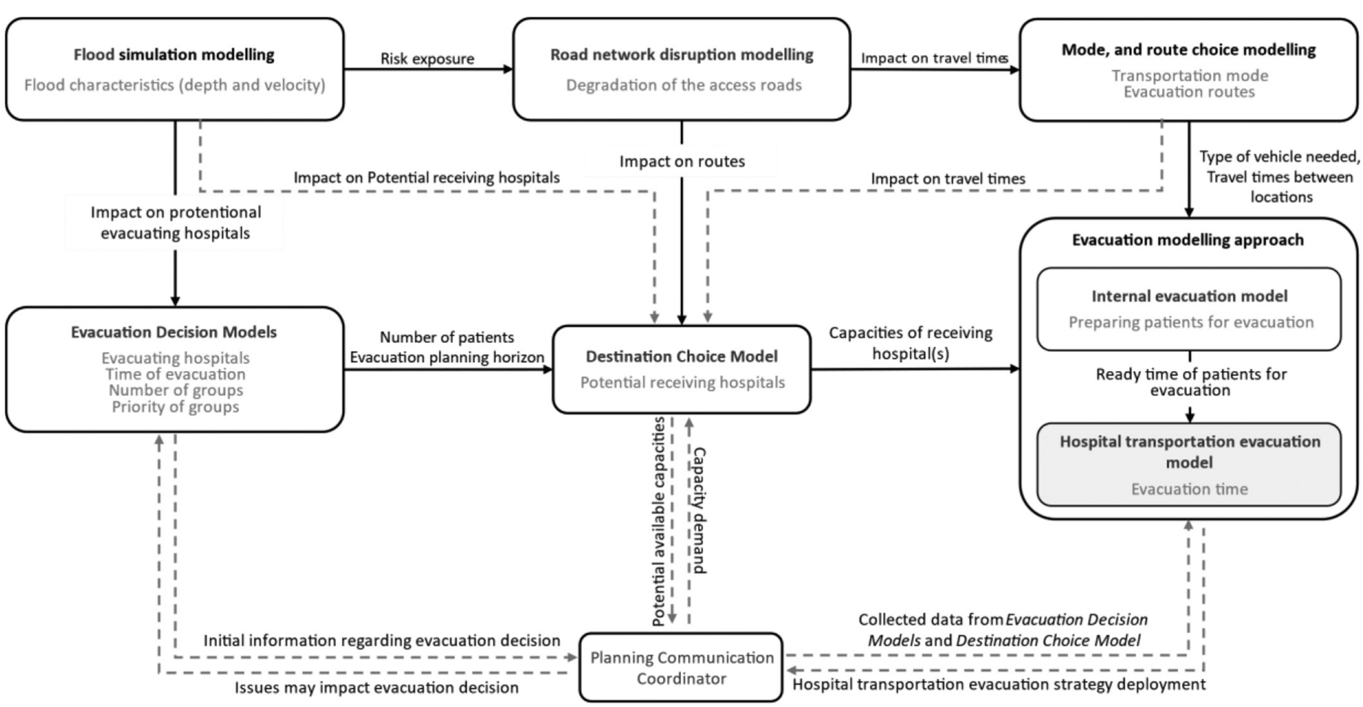

Fig. 3. A framework to design an evacuation support system for healthcare infrastructure in response to major flood events.

Table 2
Summary of recognised software/models capable of modelling flood inundation adopted from Teng, Jakeman, Vaze, Croke, Dutta and Kim [65].

Developer	1D	2D	1D + 2D	3D	Status
Ambiental		Flowroute-i			Commercial
Australian National University & Geoscience Australia		ANUGA Hydro			Open source
BMT WBM	TUFLOW Classic 1D	TUFLOW Classic 2D TUFLOW GPU, TUFLOW FV	TUFLOW Classic	TUFLOW FV	Commercial
Cardiff University	FASTER	DIVAST, DIVAST-TVD			Research
CH2M Hill (formerly Halcrow Group)	Flood Modeller Pro 1D solvers	Flood Modeller Pro 2D solvers	Flood Modeller Pro		Commercial
CSIRO				SPM	Research
DELTARES	SOBEK Suite	SOBEK Suite DELFT3D	SOBEK Suite	DELFT3D	Commercial
DHI	MIKE11/MIKE HYDRO River	MIKE21	MIKE Flood	MIKE 3	Commercial
Électricité de France	MASCARET	TELEMAC 2D		TELEMAC 3D	Open source
Innovyze	InfoWorks RS	InfoWorks 2D	InfoWorks ICM		Commercial
JBA		JFLOW			Commercial
Nottingham University		TRENT	TRENT		Research
Svašek Hydraulics		FINEL 2D		FINEL 3D	Commercial
Tokyo University		CaMa-Flood			Research
University of Bristol		LISFLOOD-FP	LISFLOOD-FP		Research
University of California		BreZo			Research
University of Exeter	SIPSON	UIM	UIM + SIPSON		Research
US Army Corps of Engineers	HEC-RAS	HEC-RAS 2D			Free
XP Solutions		XP2D	XPSWMM, XPSTORM		Commercial
ANSYS				CFX, Fluent	Commercial
Autodesk				Bifröst	Commercial
Blender				Blender	Open source
Chaos Group				PHEONIX FD	Commercial
DPIT				Navié Effex	Commercial
Kyushu University				Flip3D	Open source
Maxon				Cinema 4D	Commercial
Next Limit				RealFlow	Commercial
Red Giant				Psunami	Commercial
Side Effects Software				Houdini	Commercial
TU München & ETH Zürich				Mantaflow	Open source

Fang and Zio [66] used a framework to estimate the physical consequences of natural disasters on critical infrastructure (see Fig. 4), which may be adjusted to address the current problem. The model's inputs are the parameters, such as weather data, that characterise the disasters. The model has three parts. The first portion, the threat characterisation model, links disaster parameters with local environment estimate for the critical infrastructure (CI) system components. The structural fragility model determines the functional statuses of the CI system components in the second phase, and the component restoration model predicts the restoration time frames of the affected components in the last section.

Faturechi and Miller-Hooks [67] reviewed a variety of performance metrics that have been proposed in the disaster literature for evaluating and analysing disaster impacts on transportation systems (Table 3 and Fig. 5).

Selection of an appropriate disaster measure for the particular application is an important first step in system analysis. These measures can be generally categorised as risk, vulnerability, reliability, robustness, flexibility (also known as agility and adaptability), survivability, and resilience.

Table 3
Common definitions of common performance metrics from Faturechi and Miller-Hooks [67].

Measure	General definition
Risk	Combination of probability of an event and its consequences in terms of system performance
Vulnerability	Susceptibility of the system to threats and incidents causing operational degradation
Reliability	Probability that a system remains operative at a satisfactory level post-disaster
Robustness	Ability to withstand or absorb disturbances and remain intact when exposed to disruptions
Flexibility	Ability to adapt and adjust to changes through contingency planning in the aftermath of disruptions
Survivability	Ability to withstand sudden disturbances to functionality while meeting original demand
Resilience	Ability to resist, absorb and adapt to disruptions and return to normal functionality

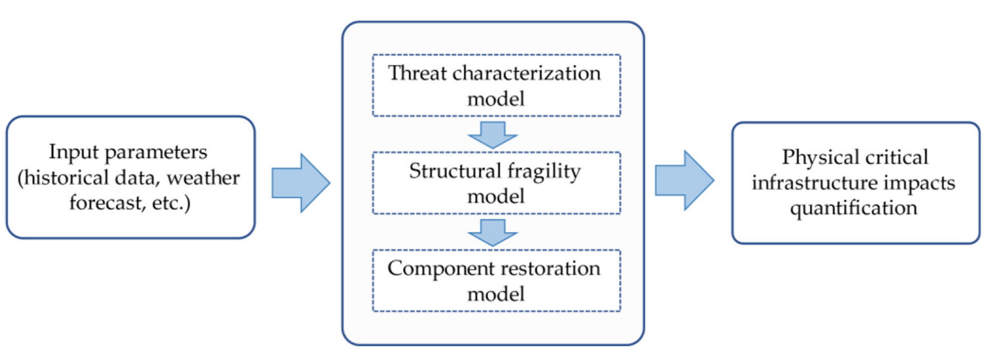

Fig. 4. A framework to quantify the physical impacts of natural hazards on critical infrastructure adopted from [66].

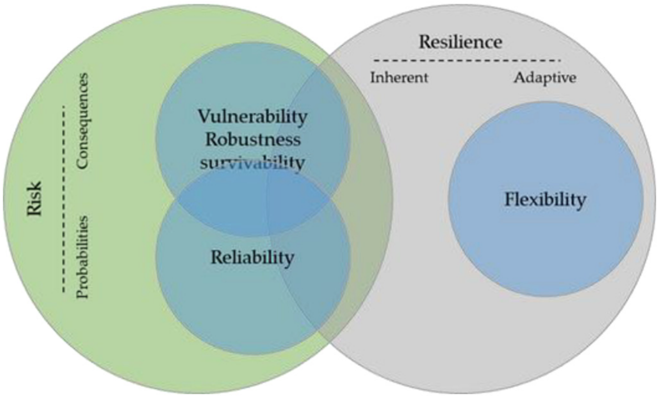

Fig. 5. Schematic of boundaries and interactions from [67].

Reviewing these performance metrics is out of the scope of this paper (readers are referred to [67].

It is expected that travel time during an evacuation will be significantly higher than the travel time under normal traffic conditions. Therefore, it is crucial to assess the travel time between two different hospitals at different departure times during the hospital evacuation. To analyse the travel times and calculate the disruption to network links from the flooding, a network model is coupled with the results of the flood simulation. Depending on the level of inundation, floodwater slows or completely interrupts traffic movement. To transition from a binary view of a flooded road, a curve proposed by Pregnolato, Ford, Wilkinson and Dawson [68] can be used. This curve relates the depth of floodwater to a reduction in vehicle speed. In addition, an inundation depth threshold $\eta_{\sqsubseteq}$ is defined for each type of rescue vehicle, and a link is assumed to be closed for vehicle type $\sqsubseteq$ when depth of flood in it is more than $\eta_{\sqsubseteq}$. Roads, for example, are considered impassable for 4WD vehicles when the flood level exceeds 600 mm [68]. Fig. 6 presents 'depth–disruption' function.

In an evacuation condition, traffic will change over time due to network congestion caused by the general population evacuation. Therefore, travel time in a network may change during the planning horizon. Tayfur and Taaffe [39] assumed that travel times in an evacuation follow a sigmoid curve that represents the behavioural response. To prove this assumption, they stated a small percentage of people start evacuating before the evacuation order, while there is a considerable increase in the number of evacuees leaving their houses when an evacuation order is broadcasted. Likewise, in this research, we have different matrixes for different time periods in which weights of two matrixes from different periods may be different. After estimating the flood depth and speed in the link $(\rangle \rightarrow |)$ at time $\sqcup$ travel time for each type of vehicle is estimated. Since travel time in a link may change during the planning horizon, the problem becomes a "time-dependent" problem; therefore, to find the shortest path between two different points, a special variant of the shortest path problem called '*Time-Dependent Shortest Path (TDSP)*' needs to be employed.

4.2. Hospital evacuation decision modelling

In Fig. 3, the centre level depicts the key factors that influence hospital evacuation decision-making. All of the components in this level play a role in deciding how patients are transported. The decision-making at the highest levels of government is closely linked to the scheduled time of departure. According to the situation, a decision is made. In some cases, the decision-maker is an individual, for example a hospital CEO, and in some cases governments make the decision [9]. Whether planning is performed for an actual disaster or potential emergency condition, the decision-maker should evaluate all aspects and consider risks, time, costs and uncertainties [41]. This may include making a decision on whether to evacuate the hospital in advance when a disaster is predicted. It is more reasonable to decide not to move the patients when associated risks with sheltering-in-place are less than transporting patients. In contrast, when the disaster affects the function of the hospital to provide service for patients, the facility must decide to evacuate. For example, 34 patients at a nursing home in Chalmette, Louisiana reportedly drowned after the management decided to shelter-in-place [13]. If hospital is evacuated too soon, the hospital may not be affected by the predicted disaster at all. An "unnecessary" evacuation may threaten patients with severe conditions. In addition, an unnecessary evacuation is sometimes very expensive. During Hurricane Irene in 2011, many hospitals in Manhattan preemptively evacuated after the mayor of New York City issued mandatory evacuation orders. However, in retrospect, these evacuations were unnecessary and cost millions of dollars in lost revenue since the hurricane was not as threatening as initially believed. This led to a certain degree of complacency among hospital administrators when Hurricane Sandy struck the following year. On the other hand, an early evacuation may allow the hospital to provide the scarce resources such as ambulances that might become even scarcer as the evacuation time window becomes shorter [54]. In addition, in the first step of this level some critical decisions such as the priority of patients should be made.

In an emergency situation, "triaged" can help define the best prioritisation of patients. The Centre for Bioterrorism Preparedness and Planning (2006) advised that patients with high support demands have the highest priority in a hospital evacuation. While Gray and Hebert [11] stated that advanced evacuation hospitals should follow this strategy, the Association of Perioperative Registered Nurses (AORN) [69] suggested that first all ambulatory patients should be evacuated, and then remaining patients who are non-ambulatory should be prioritised from the least to most critical.

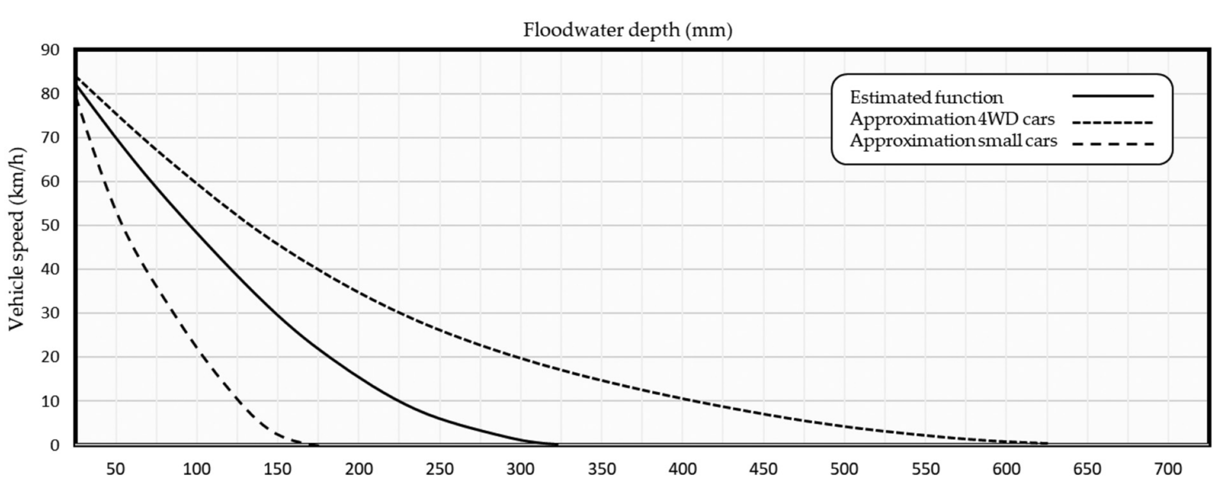

Fig. 6. The depth–disruption function that relates flood depth on the road with vehicle speed adopted from Pregnolato, Ford, Wilkinson and Dawson [68].

Johnson [70] studied prioritisation strategy by using simulation modelling and stated, "*the implicit objective at each stage is to maximize the number of people who can be moved to safety in the shortest available period of time.*" Moskop and Iserson [71] suggested that the prioritisation strategy in hospital evacuation is different from triage methods in normal conditions, therefore ambulatory patients have the highest priority compared to those who require high levels of care. Gray and Hebert [11] studied the challenges at several hospitals in Hurricane Katrina and stated that in the Lindy Boggs Medical, patients were divided into three class based on their conditions: ambulatory patients, patients that needed medical attention and critical patients. Although critical patients had the highest priority according to the hospital policy, the situation forced decision-makers to evacuate children, women and ambulatory patients first. Gray and Hebert [11] asserted "advance agreement is needed about which patients will be evacuated first."

In the next step, after finding the number of patients and their type, the number of receiving hospitals should be organised. In this step, it is very important receiving hospitals have enough capacity or capability to manage evacuated patients. For example, some of the patients from Denver Veterans Administration Medical Center were sent to a second hospital since the first host hospital they had been moved to did not have dialysis services [72]. In this step, in addition, some factors such as accessibility of hospitals during the disaster should be considered.

The last step is related to moving patients in two phases: in-building evacuation and transporting patients from the evacuating hospitals to receiving hospitals. The output of the first section, in-building evacuation, is used as an input for the transporting step. There are different approaches in the literature to estimate the evacuation times of different types of patients to support managers with their resource allocation decisions in emergency situations (e.g. [73]. The last step is the transportation phase. In this section different variants of vehicle routing problem (VRP) modelling approaches (see Fig. 7) can be modified for hospital evacuation [74]. The classical vehicle routeing problem (VRP) is formalised as a directed graph $G(E,V)$, where $V = \{0,1,\ldots,n\}$ represents the set of nodes and E represents the set of arcs. The origin is identified as node $j = 0$, and the destinations are identified as nodes $j = 1, 2, \ldots, n$, each having a demand d_j greater than zero. Each arc denotes a path from node i to node j. Each arc $C_{ij} > 0$ has a weight that correlates to the cost (time or even distance) of traveling from node i to node j. If $C_{ij} = C_{ji}$, we have a symmetric VRP; otherwise, the issue is asymmetric. From the standpoint of complexity, the classical VRP is known to be NP-hard since it generalises the Traveling Salesman Problem (TSP) and the Bin Packing Problem (BPP), both of which are well-known NP-hard problems [74]. This field of research is extremely broad, and thousands of papers have been published in this research area particularly in supply chain management and inventory routing. However, there are few hospital evacuation related models. Readers are referred to review papers such as to [75–78,80–84].

4.3. Communication planning

As presented in Fig. 3, communications, collaboration and coordination with other agencies are very important components of hospital evacuation planning. Khorram-Manesh et al. (2021) asserted that despite many publications, reports and conclusions on successful and unsuccessful evacuation, many hospitals suffer from poor communication. It increases the need for more collaboration, coordination and communication within the hospital as well as outside the hospital. Patients should be sent with their required medications and medical records. During Hurricane Katrina a psychiatric hospital evacuated very successfully since a supply of medication for all patients for ten days was packed [85]. Psychiatric patients of Denver's Veterans hospital experienced similar planning [86]. The University of Texas Medical Branch Hospital also sent medical records of patients, discharge instructions and medications of each patient [87]. In contrast, in a different experience in a Washington hospital, patients were moved with no care plans or chart document, which put the host hospital in a challenging situation [88]. Communication, particularly between hospitals, is very important in hospital evacuation [89]. As one manager of Memorial Hospital said, "you can never overcommunicate" in a disaster situation [90].

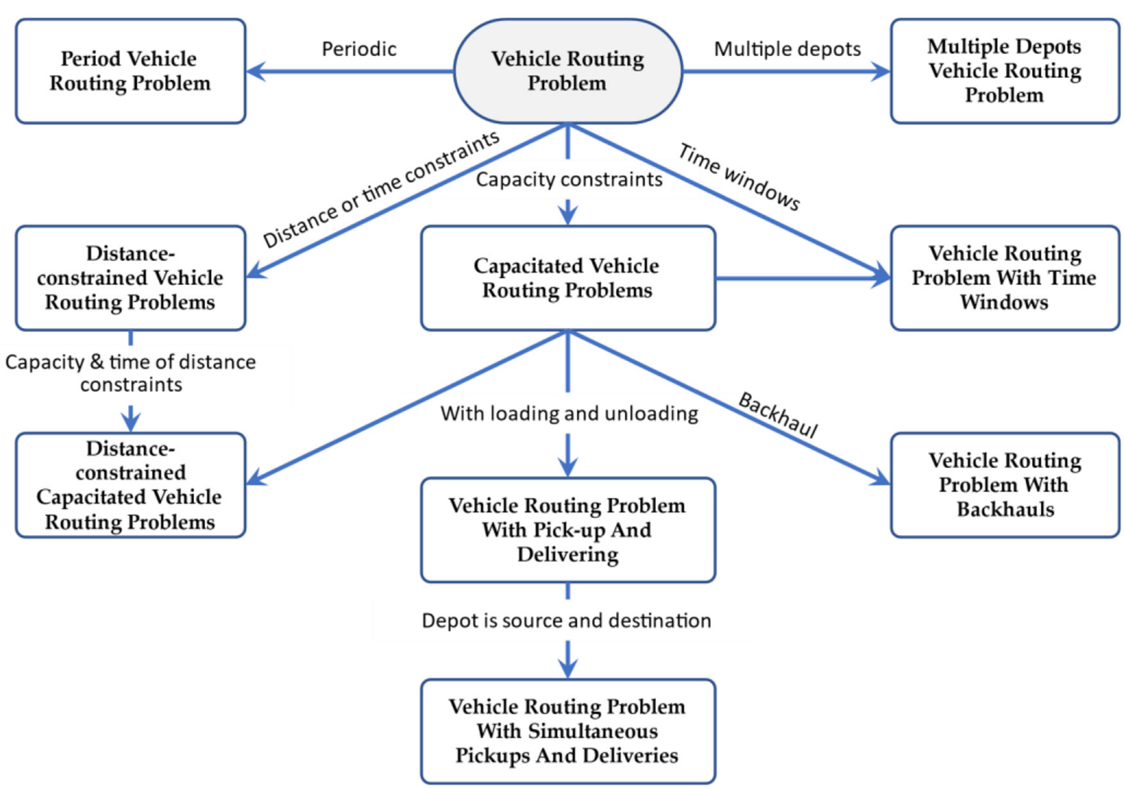

Fig. 7. Different variants of the VRP (adapted from [74]).

5. Discussions: Existing gaps and insights for future research

A closer analysis of the literature on hospital evacuation planning reveals significant research gaps to address the challenges posed by extreme flood events. Existing models can only be viewed as the first steps towards a more in-depth understanding of hospital evacuation planning in more realistic disaster situations. Many questions about mathematical formulation parameters and assumptions in a specific disaster like a flood remain unanswered. The following are some of the most important future research directions.

1) The unpredictable behaviours of floods may significantly influence the hospital transportation evacuation plan. To correctly simulate the evacuation, it is necessary to consider how the system would behave in the event of a disaster. Important considerations for effective evacuation planning and management include warning time, reaction time, information and instruction distribution, evacuation routes, traffic circumstances and traffic control measures. In the event of storms and floods, evacuation occurs before the disaster occurs, while for short-notice disasters, flood warning times are often shorter.
2) The road network is an important aspect that must not be overlooked in the development of a responsive and effective evacuation system. A flood might devastate the road network. Despite the evacuation environment typically being characterised by a wide range of uncertainties, such as road capacity reductions due to flooding [91], less attention has been paid to incorporating critical transportation network infrastructures and failure risks in hospital evacuation models.
3) One of the overlooked concepts in hospital evacuation planning is vehicle routing. Although vehicle routing is a big challenge for hospital evacuation decision-makers, there is no study on modelling and optimising vehicle routing during hospital evacuation. An efficient evacuation plan which can find the optimum route for each vehicle can play a vital role in saving lives and reducing evacuation time.
4) The majority of the mathematical models in this research area assume complete information about the problem such as travel times between hospitals, the number of patients in evacuating hospitals and the number of available vehicles and are deterministic, however, major flood events and evacuations are rare events with unusual conditions which are subject to considerable uncertainty. Although the deterministic mathematical modelling technique has been adopted by many researchers, it may not be realistic to plan a hospital evacuation with this approach.
5) Hospital evacuation planning challenges are noted for their great complexity and the need to offer optimal solutions in a short period of time. Heuristic and metaheuristic algorithms have proved effective in tackling various complicated optimisation problems. However, one of the fundamental disadvantages of current solution approaches is that parameters are deterministic, which contradicts real-world situations such as those in extreme weather event evacuations. However, there is little work on devising an effective solution approach to deal with the great uncertainties and complexity of hospital evacuation.
6) Whereas decision-makers might choose different objectives for an evacuation in different contexts, only a few objective functions have been addressed in the hospital evacuation literature. Many elements, such as the nature and intensity of the disaster, may determine the type of evacuation objective. Several objectives, such as minimising overall evacuation risk and minimising total evacuation time, have been used in the literature. In addition to these objectives, the proposed mathematical model based on the conditions can be used to achieve other objectives such as minimising the clearance time, minimising the maximum latency, minimising the total evacuation time, minimising the average evacuation time, and maximising the number of people reaching safety in a specified critical time.
7) Furthermore, although patients' unique resource needs should be included in the evacuation plan during a hospital evacuation, this aspect of hospital evacuation strategy has received little attention. During an evacuation, certain patient categories may need the coordination and use of several staff resources [49]. Whether patients are sent to a single receiving facility or numerous ones, it has been proposed that certain hospital resources, notably human resources, be moved to the new facilities in order to continue caring for patients [49].

6. Conclusions

This research is set within the context of increasing risks of flooding due to climate change and the vulnerability of many hospitals to such risks. Addressing the paucity of research into hospital evacuation transportation models, a new modelling framework has been proposed, which addresses existing model limitations by proposing key factors that should be incorporated into future hospital evacuation models to support emergency planners and decision-makers better cope with the evacuation planning challenges faced by hospitals in future flood risk scenarios.

The new model contributes to existing research and theory in the field of hospital evacuation transportation modelling by developing a holistic framework that incorporates the complexity and uncertainty associated with major flood behaviour into optimisation models. Furthermore, it developed the evacuation framework as a complex system comprised of various interactive and interdependent components such as evacuation decision models, destination choice models, and route choice modelling that can generate outputs dynamically in response to changing flood scenarios. Furthermore, from a practical perspective, the new model will enable departments of health and hospitals to better understand disaster risks, strengthen their evacuation planning, select a shelter-in-place or evacuation strategy, and equip themselves for effective response and to build back better in recovery. It can also help achieve an optimum resource expenditure balance between flood risk reduction (mitigation) and flood disaster management (response and recovery).

The approach developed in this study to model hospital evacuation transportation planning has a number of limitations. It is important to note that other factors influence evacuation plans and procedures in addition to potential transportation network failures, time limitations, and disaster modelling. Some of these factors may be considered as potential input parameters or as components in future research, such as addressing data unavailability, which continues to be a significant challenge for evacuation modelling. Even though a growing body of new empirical evidence supports the development of frameworks to model hospital evacuation planning, data for hospital evacuations remain scarce.

Despite the rich literature covered in this study, substantial research efforts remain. Other issues that may affect the success of the evacuation procedure is the difficulty in modelling the arrival time of new patients and flood behaviour. Other causes of ambiguity, such as reduced road capacity caused by floods or landslides, as well as the unpredictability of non-patient evacuee behaviour, should be studied in the future. Furthermore, this framework must be calibrated and adjusted to account for other natural hazards such as bushfires, which are common in many countries. Furthermore, this framework can be tailored to address a man-made disaster similar to the Fukushima nuclear disaster. According to the evidence, hospital evacuations during this disaster were associated with a variety of challenges [92], and at least 50 elderly patients were killed as a result of poor planning [93]. This research has created a static representation of mapped data. The creation of a visualised decision-making prototype to produce more reliable and dynamic evacuation plans promptly and effectively through online visualization would bring substantial value for strategic and operational planners. This prototype would help decision-makers run a more efficient evacuation planning procedure. This decision-making tool will give a user-friendly data input system capable of producing large amounts of data. This information might be used to determine effective evacuation routes that can be quickly and readily changed to different flood circumstances.

CRediT authorship contribution statement

Maziar Yazdani: Conceptualization, Methodology, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Mohammad Mojtahedi:** Writing – review & editing, Supervision. **Martin Loosemore:** Writing – review & editing, Supervision. **David Sanderson:** Writing – review & editing, Supervision.

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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