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A healthcare location-allocation model with an application of telemedicine for an earthquake response phase

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A B S T R A C T

Researchers have focused on finding ways of reducing natural disaster losses for decades. In recent times, technological advancements have improved the health care system and transformed emergency relief operations. An emerging medical advancement is telemedicine. The application of telemedicine has the potential to reduce the burden on the main trauma centers and hospitals after a significant earthquake occurs. The first 72 hours after an earthquake are critical. A well-planned medical response, although just one component of the disaster management process, plays a vital role in reducing mortality and morbidity. In this study, we propose a new modeling framework to optimize the selection and establishment of temporary health facilities in an area struck by a significant earthquake, and to allocate healthcare professionals, such as doctors, who can provide in-person and virtual care to the victims. The objective of the model is to minimize the total unsatisfied healthcare demand. The framework is particularly useful in low-income countries, where natural disasters quickly deplete medical and social resources. The application of the model is numerically illustrated using data from the 2005 Kashmir Earthquake in Pakistan. The results obtained are presented and discussed in the paper.

1. Introduction

After a disaster occurs, the main goal of an initial search and rescue operation is to minimize the number of fatalities. The ability of the government and relief organizations to respond promptly and effectively is crucial in saving lives. The effectiveness of the response and relief phase depends on the availability and allocation of resources [1]. Having excess resources in the field does not guarantee better operations [2]. An uncoordinated inflow of supplies will cause duplication of work and effort, resulting in unessential logistics burden, whereas a coordinated approach ensures the resources are allocated in an efficient manner [3]. One of the main difficulties arising during this phase is the optimal assignment of scarce resources to the affected areas. Unlike floods, hurricanes, tornadoes and volcanic eruptions, earthquakes are completely unpredictable [4]. After a natural disaster, the death toll can only be minimized by optimizing the treatment of the injured people [5]. The process of efficient extrication, stabilization and rescue of the wounded victims in large-scale disasters is the cornerstone of emergency medical services. A strong earthquake destroys the infrastructure, including the local pharmacies, hospitals and medical centers in the affected area. The affected regions require the establishment of temporary health facilities (THFs) that can provide trauma and emergency care services [6]. Permanent health facilities operate before the disaster occurs and continue to work for a long-term or indefinitely. The establishment of THFs, on the other hand, is a tactical or post-disaster operational decision. These THFs have a short-term horizon and can only be functional when the location of the disaster is known [7]. In large-scale disasters, supply chain configurations that have the option of establishing temporary hubs are always less costly than having the same number of permanently fixed hubs [8]. Such models provide the flexibility of choosing not to open a temporary facility and use the permanent facilities already in the configuration if needed.

Disasters are often associated with faulty logistics. The uncertainty of a disaster further aggravates the complexity of medical emergency response process. This study seeks to address the issue of establishing THFs and allocating healthcare professionals (such as medical doctors) who can provide in-person treatment or telemedicine services at these health facilities, by developing an optimization model that can be used in the event of an earthquake. The proposed methodology operates in two stages. The first stage proposes an optimization model to determine the number and location of THFs, along with the assignment of healthcare professionals to those facilities. Supply chain configurations

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with the option of temporary facilities are always more cost-effective and flexible than having the same number of fixed facilities alone at a disaster site [8]. The second stage empirically tests the model using data from the 2005 Kashmir Earthquake, which devastated large parts of Northern Pakistan and Pakistan-administered Kashmir. At least 73,000 people died, 128,309 people were severely injured and 600,000 houses were destroyed during the disaster, leaving approximately 3.5 million people homeless [66]. It is common to see that in low-income countries, people live in badly constructed houses in disaster-prone areas due to the low cost of land [9]. The disastrous earthquake destroyed 574 health facilities and caused extensive damage to roads and the infrastructure [10]. From the health emergency perspective, the initial priority was to minimize mortality and morbidity. It required evacuating the injured and establishing an efficient system to control the diseases and provide healthcare treatment to the disaster victims. However, the overcrowding of the displaced population, inadequate sanitation, contaminated drinking water and scarcity of food caused outbreaks of respiratory tract infections, diarrhea and other diseases [11]. Emergency health facilities and trauma centers were established in makeshift accommodations haphazardly without considering the demand for medicines and healthcare professionals in the affected areas [12]. Dr. Azhar Rafiq, a researcher and physician for a NASA Research Partnership Center in Virginia, mentioned in his logs, "Helicopters brought in 20 to 30 patients at a time, with little or no screening. All the area hospitals were overflowing. With telemedicine, they could have anticipated the level of injuries en-route to the hospitals" [13].

Although telemedicine has the potential to transcend geographical barriers that hinder healthcare delivery in an emergency situation, Pakistan, unfortunately, has not been able to achieve any significant benefit from these advancements [14]. A nationwide survey conducted by Ahmed and Ahmed [14] to assess the awareness of the doctors about telemedicine showed that almost 63% of them were unfamiliar with telemedicine technology. With the spike of COVID-19 cases in Pakistan, the doctors have started to become aware of and transition towards telemedicine [15]. The federal government is getting involved in the development and support of telehealth, by initiating programs such as Yaran-e-Watan, in which Pakistani diaspora are encouraged to provide telehealth services during the pandemic [16].

We contribute to humanitarian logistics literature by addressing the following gaps in the literature. First, this research study is pioneering the use of a computationally efficient optimization model to analyze a temporary healthcare facility-location problem post-disaster, specifically after an earthquake. The proposed model is linear, and it takes on average only twenty seconds to solve the model and find the optimal solution. Second, it incorporates telemedicine in the disaster response phase and focuses on the allocation of health professionals to the demand points who are trained to use telemedicine. Our analysis shows that such a response mechanism may provide substantial support to humanitarian response operations. Third, it considers the demand for medical services based on the profile of injuries arising after an earthquake and medical triage. Fourth, to the best of our knowledge, there are no studies on optimization models developed in the area of emergency management that utilize any earthquake data from Pakistan.

This paper is organized as follows. Section 2 provides a review of the current literature, followed by a conceptual framework in Section 3. Section 4 describes the model formulation, which includes the model assumptions, notation, and the mathematical model. Section 5 elaborates on the applications of telemedicine in disaster response phase in Pakistan to show the relevance of the proposed optimization model. A numerical case study describing a hypothetical THF-based response to the 2005 Kashmir Earthquake in Pakistan is presented in Section 6. A sensitivity analysis of the case study is provided in Section 7. Section 8 consists of a two-stage stochastic programming framework, followed by conclusion in Section 9.

2. Literature Review

This section starts with an overview of the phases of humanitarian logistics and modes of telemedicine service delivery, followed by a review of literature covering prepositioning of healthcare staff, healthcare facility location and telemedicine in the sub-sections.

2.1. Background

There are four phases of humanitarian logistics management: mitigation, preparedness, response and recovery. Mitigation is an ongoing effort that occurs before the disaster to reduce the physical and social impact of disasters on the community. There are two types of mitigation: *structural mitigation*, which encompasses designing and building of infrastructure to cope with and resist the physical impacts of disasters, whereas *nonstructural mitigation* involves the process of reducing the human and infrastructure exposure to the hazard of disasters [17]. Preparedness also occurs before the occurrence of disasters and includes prepositioning of assets and resources to facilitate the logistics process following a disaster [18]. Both response and recovery take place after a disaster occurs. Disaster response provides for immediate protection of life and health of the disaster victims, and recovery involves both short-term reestablishments of physical and social systems, along with the long-term efforts to restore the systems to their pre-disaster state [19].

There are two main modes of delivering telemedicine services: *store and forward telemedicine (asynchronous)* is a method in which healthcare providers share the patient information to other healthcare providers as digital images, videos and documents, which can be accessed at a later date, whereas in the second type of telemedicine, i.e. *real-time (synchronous) telemedicine* also called live telemedicine, patients and physicians can share real-time information via live video conferencing or digitized medical instruments that allow live monitoring of patients [20].

Studies by Balcik and Beamon [21]; Rawls and Turnquist [22]; Taskin and Lodree Jr [23]; Rawls and Turnquist [24]; Salman and Yücel [25]; Pradhananga et al. [26]; Stauffer et al. [8]; Baskaya et al. [27]; Yahyaei and Bozorgi-Amiri [28] were centered on the prepositioning of resources to minimize cost. Studies focusing on location facility and allocation of resources for post-disaster phase include Barbarosoğ;lu and Arda [29]; Bozorgi-Amiri et al. [30]; and Döyen et al. [31]; Zokaee [32] with the goal of cost minimization. Contrary to the popular approach of minimizing costs, Rennemo et al. [33] aimed to maximize utility expressed in terms of demand fulfillment and residual monetary budget. This study proposed a stochastic model for disaster relief and response phase to achieve a fair distribution of aid [33]. Another study conducted by Maharjan and Hanaoka [7] focused on an optimization model with the objective of minimizing total unsatisfied demand for emergency relief materials. Trivedi and Singh [34] propose a multi-objective shelter site location-relocation model to minimize distance, risk, number of facilities and unmet demand while simultaneously maximize suitability using goal programming approach.

2.2. Prepositioning of Healthcare Staff

Rodríguez-Espíndola, Albores, and Brewster [2] introduced a multi-objective optimization model for flood preparedness to determine the location of emergency facilities (pre-disaster), stock prepositioning, resource allocation and relief distribution. The objective function minimized the cost associated with these activities. One of the performance measures incorporated in the model was fulfilment rate, which was based on the fulfilment of relief items, the availability of healthcare staff for providing medical services to the injured and the presence of shelter staff who are responsible for security, cooking and other activities. The study used data from the 2013 flood of Acapulco, México and concluded that having excess resources in the field does not guarantee better operations. In another study, researchers state that finding the optimum level of resources and resource combination can yield the best results [35].

2.3. Healthcare Facility Location

There is abundant research on facility location problems for product distribution in the literature, and many models exist to solve location problems. However, the methods and models developed in the vast majority of the previous studies are applicable to all types of disasters [36]. Studies on facility location planning have mainly focused on facility location as a part of the pre-disaster operation [37]. In an uncertain dynamic disaster environment, it is plausible to consider facility location modeling as a part of the post-disaster process. Emergency health facilities provide health aid and medical treatment to the individuals affected by large-scale disasters. Determining the location of these facilities and establishing them promptly can play a vital role in saving lives [34]. Trivedi and Singh [38] note that the problem of establishing health facilities are addressed in a limited number of studies. Caunhye et al. [37] suggest in their study to initiate research in terms of temporary relief and treatment centres to help the victims after disasters as there is no study in this domain.

2.4. Telemedicine – health technology

Telemedicine is the delivery and provision of health-related services and consultation by the provider to the patient via electronic information and telecommunication technologies. The continued evolution of smart devices and new technologies provides opportunities to offer telemedicine services around the world and presents enormous potential to improve the quality and efficiency of healthcare services at a reduced cost [39]. Telemedicine technology includes the electronic data acquisition, processing, distribution, and storage of information with the objective of health promotion, disease prevention, treatment of the sick, and management of illnesses and protection of public health [40]. Telemedicine systems consist of a collaborative network of healthcare providers and facilities to achieve these goals. The automation of the process of triage and patient prioritization in a telemedicine environment can greatly improve the quality of medical treatment and hospitalization of the patients [41].

In earthquakes, the priority in the relief operation is to rescue the injured people and provide them with medical treatment within the first 72 hours of the disaster [36]. Telemedicine is an effective and cost-saving alternative to the traditional mode of healthcare delivery system. Health personnel can handle more patients than conventional healthcare systems would typically allow, by using essential electronic equipment to access other specialized doctors [42]. Telemedicine has the potential to improve access to all levels of healthcare, reduce costs, and increase the efficiency of diagnosis, prescription and treatment of patients [40].

2.5. Research issues and objective of the study

A significant earthquake is defined as a destructive earthquake with a magnitude of 7.5 or higher (on the Richter scale), which causes at least $1 million in damages and results in at least 10 deaths, or generates a tsunami [43]. The two major differences between significant disasters and other regular emergencies are the low frequency of large-scale emergencies (in contrast to regularly occurring emergencies), and the sudden tremendous demands which overwhelm the emergency responders [44]. In this study, we propose a modeling approach to optimize the selection and establishment of THFs in the areas affected by a significant earthquake. The quantitative model can be used to allocate healthcare personnel to these THFs optimally. The objective of the study is to minimize the total weighted unsatisfied healthcare demand for earthquake victims.

Caunhye et al. [37] reviewed optimization models developed in the area of emergency logistics and proposed a set of guidelines for the researchers to explore new avenues in this field. The authors advised that future studies can focus on the establishment of relief and medical treatment centers after a disaster occurs. Research until now has considered facility location as a part of the pre-disaster process [37]. In an uncertain dynamic disaster environment, it is reasonable to assess the viability of establishing THFs post-disaster. In this study, we use their framework as the basis of our model and modify it according to our research questions. We specifically address the following research questions:

- What is an optimal approach of locating a THF and allocating medical staff to these facilities?
- How can telemedicine be incorporated into an earthquake response phase?

3. Conceptual Framework

The conceptual framework in Figure 1 shows the activities and the phases of the disaster (an earthquake in this case). Since earthquakes are unpredictable, the disaster sites are unknown before the disaster, and only the information about potential disaster sites is available. Pre-disaster operation includes capacity planning and telemedicine training of healthcare personnel. Once the information about the earthquake sites become available, then the post-disaster operation begins. Post-disaster relief process comprises of the establishment of THFs on the disaster sites and allocation of healthcare personnel to those sites, which is the focus of this study. Models that have the option of opening temporary facilities are always less costly than using the same number of fixed facilities because these models can always choose not to open temporary facilities and use the fixed facilities if they are operational [8].

Caunhye et al. [37] mention that previous studies have not taken the seriousness of injuries into account. The authors recommend that models comprising of medical facilities should add in slack to align service capacity with demand for medical treatments via the addition of healthcare personnel and equipment. In this study, we have addressed this issue by adding a new resource element to the framework: 'well--equipped, out-of-range hospitals' (referred to as remote hospitals), which are far away from the disaster site but still support the THFs through telemedicine. Telemedicine is a practical and cost-saving approach of providing healthcare services to the injured people, and it has the potential of reducing the load on main trauma centers.

4. Model Formulation

In this section, we introduce the location-allocation model, which consists of deterministic variables. We consider the response phase of a significant earthquake when the time and budget are limited, a large number of people are affected, and considerable infrastructural damage occurs, resulting in unavailability of healthcare facilities and hospitals.

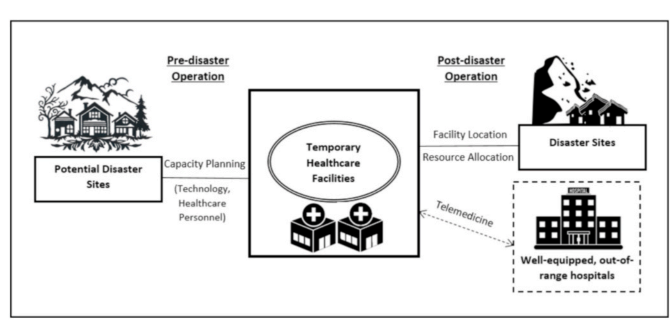

Fig. 1. Conceptual framework.

The facility location objective for large-scale emergencies (such as a significant earthquake) should be carefully defined because such disasters are bound to impact lives. The stakes are high in healthcare, including telemedicine, when a doctor tries to diagnose an illness or provide medical treatments to the patients. Therefore, investment in appropriate and suitable technology is essential in the area of telemedicine [45]. Although the incorporation of telemedicine in the model increases the number of variables and constraints, it still remains a linear and tractable problem.

Effective disaster response requires the establishment of THFs that can provide medical services to the affected people. Each demand point or district ‘j’ has an associated demand for emergency medical services. The affected areas of the disaster are known before the decision of establishing a THF is made. With the selection of THFs, the model determines whether high-level or low-level of telemedicine technology will be installed at location j. The category and number of health professionals assigned to each THF are also identified. The assumptions of the model are mentioned below:

4.1. Model assumptions

A set of assumptions underpinning the model is established in order to limit the scope of the problem area and have a tractable set of variables.

- An unrealistic assumption in many of the papers on the prepositioning of resources is the availability of infinite available resources [36]. However, many factors limit the availability of resources. In this paper, we assume that there is a limited budget, which is known, and it can be utilized to establish THFs, to spend on the healthcare staff training in telemedicine, and to install telemedicine equipment at the THFs.
- The fundamental premise of telemedicine is the availability of and access to voice and data communication that allows the medical services to be delivered remotely. The model assumes that the responders at the location of an earthquake can immediately establish telemedicine linkages using the primary telecommunication devices. It would potentially ensure quick response and increase the capacity of medical services provided to the people when required. This is a simplifying assumption and, if there is a delay in the restoration of telecommunication infrastructure after the disaster, there will be a delay in the use of telemedicine. However, the model is flexible enough to accommodate this delay by reducing α and β values, which depict the rate of health service delivery using high-level and low-level telemedicine technologies, respectively.
- Demand for medical services can be divided based on the profile of injuries arising during an earthquake. Patients that need urgent and special care due to severe injuries are categorized as ‘critically injured/critical’. Their survival time is shorter than those who are mildly injured and classified as ‘non-critical’. This categorization of patients is based on a study by Xiong et al. [46].
- We consider two levels of telemedicine to provide medical services. The first level consists of advanced telemedicine devices that can be used by physicians to share real-time health information of the patients with specialists in remote hospitals via live video conferencing or digitized medical instruments, allowing live monitoring of patients. This level of telemedicine has been categorized as ‘high-level telemedicine technology’ in the model, and it is provided to those patients who are categorized as critically injured/critical. The second level consists of basic telemedicine tools categorized as ‘low-level telemedicine technology’, and it is used to help non-critical patients [47]. A low-level telemedicine technology consists of basic telemedicine equipment such as a transportable exam station, which is suitable for emergency relief [48]. A high-level telemedicine technology consists of advanced medical equipment, which includes telemedicine peripherals (peripherals are diagnostic tools used in telemedicine) [49].
- There are two types of physicians: generalists (general practitioner) and specialists [50]. Generalists can provide medical care to non-critical patients who do not require any specialized medical treatment or surgery. Whereas specialists are capable of treating critically injured patients; therefore, in our model, we assign them to handle critical patients only.
- The nature of injuries and demand for the physicians is unknown before the disaster. We assume that the healthcare personnel would be provided with general telemedicine training before the disaster. When the disaster occurs, the demand values become known, and the process of skills assessment begins. Based on the post-disaster evaluation, the healthcare personnel can be provided a short training based on the available information and required hardware/software needs. The Center for Disease Control and Prevention – CDC refers to this process as ‘pre-deployment training’ [51]. In Section 8, we modify this assumption to study situations where telemedicine training can only be performed pre-disaster.
- Generalists who are trained to operate high-level telemedicine technology are assumed to have access to specialists in remote hospitals. This allows them to help critically injured patients - but at a slower rate than in-person specialists as indicated by α in the objective function. Generalists trained to utilize low-level telemedicine technology are assumed to treat non-critical patients but at a faster rate than untrained generalists as indicated by β in the objective function. This is a reasonable assumption because trained generalists can utilize digitized medical instruments that can assist them with the treatment procedure.

4.2. Notation and definitions

To formulate the model for significant earthquakes, we consider a set J of affected areas as demand points. Indexed on this set, the following input parameters and decision variables are defined:

Index set

J Set of affected areas; $j \in J$

Input Parameters

θ The importance triage-weighted factor based on the injury profile of the patients
α Rate of health service delivery by trained generalists who can use high-level of telemedicine technology as compared to the specialists
β Rate of health service delivery by trained generalists who can use low-level of telemedicine technology as compared to the untrained generalists
$d_{j(s)}$ Number of doctors needed who can provide specialized treatments for critical patients at location j
$d_{j(m)}$ Number of doctors needed who can provide general medical treatments for non-critical patients at location j
$n_{(s)}$ Number of in-person specialist doctors
n Total number of generalists
c Cost of establishing one THF at location j
H Available budget for establishing THFs
$u_{(htg)}$ The unit cost of training a doctor to use high-level telemedicine technology
$u_{(ltg)}$ The unit cost of training a doctor to use low-level telemedicine technology
T Available budget for telemedicine training of the doctors
$v_{(ht)}$ The unit cost of setting up high-level telemedicine at a THF
$v_{(lt)}$ The unit cost of setting up low-level telemedicine at a THF
L Available telemedicine installation budget

Decision variables

$q_{j(s)}$ Number of specialists assigned to location j
$q_{j(htg)}$ Number of trained generalists assigned to location j, which has high-level of technology
$q_{j(ltg)}$ Number of trained generalists assigned to location j, which has low-level of technology
$q_{j(g)}$ Number of untrained generalists assigned to location j
y_j A binary variable that equals 1 if a THF is established at location j, 0 otherwise
$x_{j(ht)}$ A binary variable that equals 1 if high-level of telemedicine technology is installed at location j, 0 otherwise
$x_{j(lt)}$ A binary variable that equals 1 if low-level of telemedicine technology is installed at location j, 0 otherwise
$n_{(htg)}$ Number of trained generalists who can use high-level of telemedicine technology
$n_{(ltg)}$ Number of trained generalists who can use low-level of telemedicine technology
$n_{(g)}$ Number of generalists untrained in telemedicine

4.3. Mathematical Model

In what follows, we present the mathematical model, an integer linear program. A demand point can be partially or fully covered based on the availability of doctors and healthcare demand in the affected area.

Minimize:

$$Z=[\theta]\sum_j\left[d_{j(s)}-q_{j(s)}-(\alpha)q_{j(htg)}\right]+[1-\theta]\sum_j\left[d_{j(m)}-q_{j(g)}-(\beta)q_{j(ltg)}\right] \quad (1)$$

Constraints:

$$u_{(htg)}.n_{(htg)}+u_{(ltg)}.n_{(ltg)} \le T \quad (2)$$

$$n_{(htg)}+n_{(ltg)}+n_{(g)} \le n \quad (3)$$

$$\sum_j c\ y_j \le H \quad \forall j \in J \quad (4)$$

$$x_{j(ht)}+x_{j(lt)} \le y_j \quad \forall j \in J \quad (5)$$

$$v_{(ht)}\sum_j x_{j(ht)}+v_{(lt)}.\sum_j x_{j(lt)} \le L \quad \forall j \in J \quad (6)$$

$$q_{j(s)} \le n_{(s)}.y_j \quad \forall j \in J \quad (7)$$

$$q_{j(htg)} \le n.x_{j(ht)} \quad \forall j \in J \quad (8)$$

$$q_{j(ltg)} \le n.x_{j(lt)} \quad \forall j \in J \quad (9)$$

$$q_{j(g)} \le n.y_j \quad \forall j \in J \quad (10)$$

$$\sum_j q_{j(s)} \le n_{(s)} \quad \forall j \in J \quad (11)$$

$$\sum_j q_{j(htg)} \le n_{(htg)} \quad \forall j \in J \quad (12)$$

$$\sum_j q_{j(ltg)} \le n_{(ltg)} \quad \forall j \in J \quad (13)$$

$$\sum_j q_{j(g)} \le n_{(g)} \quad \forall j \in J \quad (14)$$

$$d_{j(s)}-q_{j(s)}-\alpha.q_{j(htg)} \ge 0 \quad \forall j \in J \quad (15)$$

$$d_{j(m)}-q_{j(g)}-\beta.q_{j(ltg)} \ge 0 \quad \forall j \in J \quad (16)$$

$$\begin{aligned}&0 \le \alpha \le 1,\ \beta \ge 1,\ 0 \le \theta \le 1\\&y_j,\ x_{j(ht)},\ x_{j(lt)} \in \{0,\ 1\}\ \forall\ j \in J,\\&q_{j(s)},\ q_{j(htg)},\ q_{j(ltg)},\ q_{j(g)} \ge 0 \text{ and integer } \forall\ j \in J,\\&n_{(htg)},\ n_{(ltg)},\ n_{(g)} \ge 0 \text{ and integer.}\end{aligned} \quad (17)$$

The objective function (1) minimizes total weighted unsatisfied healthcare demand. The triage weighted parameter, θ, is used to prioritize the urgency of medical treatment based on the profile of the injuries of the patients. It is a common practice in disaster management to divide injured people into groups such as patients in need of emergent care, and patients not in need of emergent care [52]. Constraint (2) ensures that the total cost of training the doctors to use telemedicine is less than or equal to the available budget for the telemedicine training. Constraint (3) ensures all the trained and untrained generalists are less than or equal to the total number of the generalists available. Constraint (4) ensures that the available budget for establishing THFs is not exceeded. Constraint (5) ensures that if a THF is established at a demand point, it can have no telemedicine technology, a low-level telemedicine technology, or high-level telemedicine technology based on the demand for each type of doctor (i. e. the telemedicine technology will be at one of three levels: none, low, or high). Constraint (6) ensures that the total cost of setting up telemedicine at the THFs is less than or equal to the available telemedicine installation budget. The limitations on the availability of specialists, trained generalists who can use high-level of telemedicine, trained generalists who can use low-level of telemedicine and untrained generalists at a THF are represented by Constraints (7), (8), (9) and (10) respectively. Constraints (11), (12), (13) and (14) represent the availability of the doctors across the whole network. Constraints (15) and (16) make sure that the number of health professionals assigned to location j does not exceed the demand for them. Constraint (17) expresses the nature of the decision variables used in the model.

5. Applications of Telemedicine in Disaster Response Phase

5.1. Worldwide Practices

In this section, we provide the essential background information about the application of telemedicine in the disaster response phase around the world. The practice of utilizing telemedicine during the rescue and response phase of disasters became popular in the mid-1980s, following the devastation of the 1985 Mexico City earthquake [46]. NASA provided advanced satellite communication technology to provide support to the medical relief activities after a significant earthquake of magnitude 8.0, struck the greater Mexico City area [53].

In December 1988, a significant earthquake shattered the north of Soviet Armenia, killing 60,000 people and destroying nearly half a million buildings [54]. NASA provided telemedicine technology to aid Armenia in recovering from the disaster. Telemedicine was used in the post-disaster recovery phase of this incident, and it took NASA a number of months to implement such a large-scale project to provide medical services to the victims of the disaster [55]. Following the disaster, the country continued to utilize and invest in telemedicine, by establishing several telemedicine organizations such as HYEBridge, American Telemedicine Association and the Armenian Association of Telemedicine – AATM [55]. Several years later, a major gas explosion occurred in Ufa, the capital of Bashkir Republic. The NASA-led telemedicine project was adopted and implemented by using telephone lines to provide consultative support to the burn victims by the local doctors with the virtual assistance of specialists [56].

NASA's groundbreaking and pioneering work in telemetry and use of satellite technology demonstrated the utility and capability of telemedicine in the event of natural disasters, and it resulted in the practices that we are accustomed to today. Remote communication and collaboration allow medical staff to make a diagnosis, treat the patients and even conduct surgeries without meeting the other parties involved. Recently, telemedicine has been used in numerous ways in response to natural disasters including earthquakes, hurricanes and tsunami [57–60].

5.2. Pak-US Collaboration: Telemedicine training project

The first telemedicine project in Pakistan, the TelMedPak project, was initiated in 1998 with the collaboration of a U.S. based company, Elixir Technologies [61]. A training program for the doctors of Pakistan in the field of telemedicine was arranged in the USA, before the 2005 Kashmir Earthquake [62]. The purpose was to train a few master trainers who can go back to the country and train more doctors in this field. The country needs more trained telemedicine professionals who can assist in future telemedicine projects. A telemedicine training center was established in the 'Holy Family Hospital' in Rawalpindi, one of the major cities of Pakistan. The trainers have developed training manuals and telemedicine software, and they train regional medical staff [63].

5.3. Role of Telemedicine in Disaster Management in Pakistan

When the 2005 earthquake struck the areas of Pakistan, there were physicians, trained telemedicine personnel and the required equipment to respond to the disaster. Even though telemedicine was used on a limited scale in that event, it was of great benefit in reducing the damages of the disaster [62,63]. The telemedicine center in 'Holy Family Hospital' acted as a telemedicine hub, which established mobile telemedicine units in the affected areas of Muzaffarabad, Balakot, Pindigheb and Attock [63].

5.4. Health Capacity Development through Telemedicine in Pakistan

Pakistan is prone to violent earthquakes as the country is located on both the Eurasian and Indian tectonic plates [64]. The current trained telemedicine healthcare professionals are limited in number and can only serve the needs of two cities of Pakistan: Islamabad and Rawalpindi. There is an urgent need of trained telemedicine personnel to cater to the needs of the other parts of the country [63].

6. Numerical Illustration

We illustrate the usefulness of this model with a numerical example using disaster data from the 2005 Kashmir Earthquake in Pakistan. The case study is small enough to be solved in a comprehensive form with a commercial software program but thorough enough to be of interest as an illustration, to validate the model. On the tranquil morning of October 8, 2005, while most people were asleep, an earthquake of magnitude 7.6 on the Richter scale jolted the northern parts of Pakistan, which include the Pakistan-administered portion of the Kashmir region (Azad Jammu and Kashmir - AJK) and the Khyber Pukhtunwa (KPK) province [65]. Pakistan is prone to numerous types of natural disasters such as floods, earthquakes, landslides, droughts and cyclones [66]. However, the devastation caused by the 2005 earthquake eclipsed all the past catastrophes. The earthquake destroyed numerous cities and villages, causing extensive damage to the roads and the infrastructure. Most hospitals and medical centers were damaged, and a limited number of health facilities were available to provide medical treatment to the affected population [12].

In this section, we study the three districts that bore the brunt of the earthquake. Each district is further sub-divided into three tehsils. These nine tehsils serve as the demand points in the model. Table 1 provides the breakdown of the states, districts and tehsils (see Table 2).

Muzaffarabad and Balakot were two of the hardest-hit areas in Pakistan. As shown in Figure 2, the epicenter of the earthquake was just northeast of Muzaffarabad, and it ruptured the Balakot-Bagh fault [67].

Table 1
Administrative divisions of the affected area.

Area Most Affected	District	Demand Points	Tehsils
KPK	Mansehra	1	Balakot
		2	Mansehra
		3	Oghi
AJK	Bagh	4	Bagh
		5	Dhirkot
		6	Hari Ghel
AJK	Muzaffarabad	7	Muzaffarabad
		8	Nasirabad
		9	Garhi Dopatta

Table 2
The data was retrieved from NDMA [69] and Mulvey et al. [68].

Districts	Total Number of Casualties	Total Number of Injured People	Injured People – The First 72 Hours
Muzaffarabad	34,173	56,526	3,538
Mansehra	24,511	35,306	2,210
Bagh	8,157	24,000	1,502

In a small village in the Bagh district, Forward Kahuta, one hospital remained functional, which was flooded with injured people [68]. The hospital was staffed by 4 specialists and 14 generalists [68]. It was a military hospital; therefore, it was well equipped for emergencies. However, the scale of injuries caused by this earthquake was well beyond the normal emergency response capabilities of the hospital. Due to a large number of patients and damage to the transport infrastructure, it became challenging to transfer them to the referral hospitals, which resulted in a large number of casualties. During the first 72 hours, 1506 patients were triaged into two groups; 472 patients were deemed as critical, and 1034 patients were considered non-critical [68]. Due to the lack of medical staff and unavailability of health facilities, treating all the patients became an unmanageable task.

The number of injured people, critical and non-critical, was obtained for the first 72 hours of the relief phase. This was translated into the demand for health professionals needed at the disaster sites. A physician can see between 11 and 20 patients per day, based on the seriousness of injury or illnesses of the patients [70]. To translate the number of critical and non-critical patients into the demand for health professionals, we divide it by 10 and 15 respectively, assuming that a specialist can treat 10 critical patients and a generalist can treat 15 patients in an emergency situation, with limited resources. A trained generalist who can use high-level or low-level telemedicine will be able to treat more patients, depending on the value of α or β respectively. Cost of establishing a THF

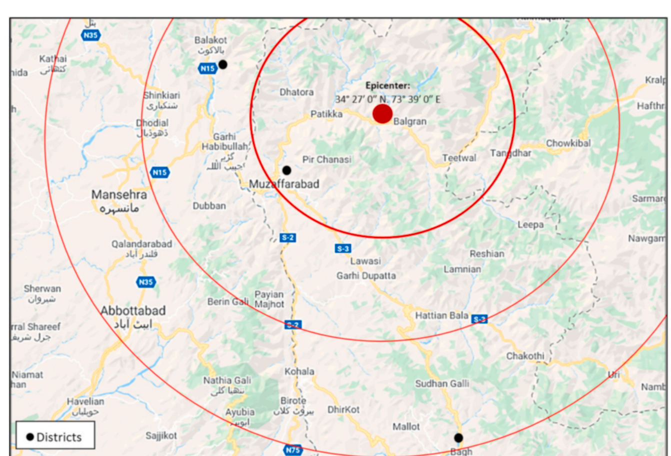

Fig. 2. Azad Kashmir and Khyber Pakhtunkhwa, Pakistan.

and training a doctor to use telemedicine technology was based on discussions with an architect and a medical specialist located in Quetta, Pakistan. Cost of installing telemedicine technology at a THF was acquired from AMD Global [71]. Although our model can accommodate different values of the cost of establishing THFs at various locations, in this case, we consider the same level for the parameter 'c' for the three districts based on the similarity of physical geography, terrain and weather conditions of the regions. A summary of cost and budget-related parameters is presented in Table 3.

We have nine demand points, so we can establish a THF at any or all of these locations based on the available budget for establishing THFs. During the relief phase of the 2005 earthquake, aid workers and doctors were taken to the disaster sites via helicopters. As the number of healthcare professionals (specialists and generalists) is considerably less than the number of injured people, we assume that all the healthcare professionals can be transported to the affected areas via helicopters without any delay. It is more feasible to take doctors to the disaster sites than to carry a large number of injured people in critical condition to the hospitals outside the area. A resident of Balakot named Ali suffered a crush injury to one of his arms after his house collapsed on him [12]. Due to the limited number of helicopters, he had wait to be airlifted and transferred to a hospital. Due to the prolonged disruption of blood supply to the nerves, his arm could not regain movement after the treatment [12].

We solved the model using a standard solver, IBM ILOG CPLEX Optimization studio 12.9. The optimal solution to the model selects to establish a THF at demand points 1, 2, 4, 7 and 8, given the available budget for establishing THFs. The major factors in THF selection include the demand for the health professionals in the form of the number of injured people at a demand point, the cost of establishing a THF and the available budget. The detailed results are shown in Table 4, which presents the selection of demand points where THFs can be optimally established, the decision of whether a THF should have high-level, low-level or no telemedicine technology, and the allocation of four types of health professionals. Managing a limited budget and optimally allocating the resources to minimize the total weighted unsatisfied healthcare demand is the objective of the model. The weight parameter, θ, is used to prioritize the urgency of medical treatment based on the profile of the injuries of the victims of the earthquake. A higher weight is allocated to the groups of people who need emergent care, therefore θ=0.7. The rate of health service delivery to the patients in critical condition by a trained generalist who can use high-level telemedicine technology with the remote assistance of a specialist, is assumed to be lower than the specialist, and is therefore, $\alpha = 0.6$. The rate of health service delivery to the patients in non-critical condition by a trained generalist who can use low-level telemedicine technology is assumed to be higher than an untrained generalist who cannot use telemedicine, and is therefore $\beta = 1.3$.

As shown in Table 4, the selected THFs include one demand point where high-level telemedicine technology is installed, and four demand points have low-level telemedicine technology. Muzaffarabad district that consists of demand points 7, 8 and 9 has the highest number of injured people, both in critical and non-critical conditions. The solution shows that two THFs established at demand points 7 and 8 can serve the needs of the injured people in these high-demand tehsils. Followed by Muzaffarabad district, Mansehra district has the second highest number of injured people, which consists of demand points 1, 2 and 3. Demand point 1 that represents Balakot, was the hardest hit town in this district. The solution shows that there are two THFs established at demand points 1 and 2, and both THFs have low-level telemedicine technology. There is only one THF in the third district, Bagh, which consists of demand points 4, 5 and 6. This THF has a high-level of telemedicine technology, serving a large number of injured people in critical condition. Table 4 also presents the optimal allocation of four types of health professionals (specialists, trained generalists who can use high-level of telemedicine technology, trained generalists who can use low-level of telemedicine technology and generalists who are not trained in telemedicine) to the nine demand points.

Table 3
Cost and budget-related parameter values.

Parameters	Values
c	\$5000
$u_{(htg)}$	\$100
$u_{(ltg)}$	\$25
$v_{(ht)}$	\$15,000
$v_{(lt)}$	\$5,000
H	\$25,000
T	\$10,000
L	\$35,000

After a large-scale earthquake occurs, the relief wing of an Earthquake Management Authority has to respond within a limited timeframe and budget. Due to the availability of minimal information, a comprehensive but straightforward model, as proposed in this paper, can greatly help the humanitarian organization. Thus, the result of this study can be useful to a response team that is responsible for the selection of THFs and allocation of resources.

7. Sensitivity Analysis

This section elaborates on the results of the base case scenario presented in the previous section, Numerical Illustration. The effect of changing various parameters is measured on the optimal solution i.e. the objective function value. Nine parameter changes are studied as follows: two rates of health service delivery related parameters (α, β); one regarding the triage-weighted factor (θ); three budget related parameters (H, T and L); two regarding the number of health professionals ($n_{(s)}$ and n), and one cost parameter (c). Unless mentioned otherwise, each parameter is studied by keeping the other parameters the same as in the case study. The sensitivity analysis is displayed in tables and figures.

7.1. Effect of the rate of health service delivery by telemedicine professionals, α and β

To observe the behavior of the optimization model with respect to the varying levels of α and β, we generate 121 scenarios by keeping the other parameters constant. As defined in the model, the values of α can vary from 0 to 1, and β can be greater than or equal to 1, i.e. $0 \leq \alpha \leq 1$, $\beta \geq 1$. When $\alpha = 1$, the trained generalists who can use high-level telemedicine are as good as specialists and they can provide medical treatment to the critical patients at the same rate as specialists. When we decrease α to 0.6, then it implies that the rate at which a trained generalist who can use high-level telemedicine provides medical treatment to critical patients is 60% of that of a specialist. It is reasonable to assume that the trained generalists, even when equipped with high-level telemedicine technology, cannot surpass a specialist having years of experience and expertise. However, with the help of telemedicine, the generalists can now provide medical treatment to critical patients, although at a lower rate. Therefore, the value of α varies between 0 and 1. When $\beta = 1$, it indicates that the rate of service delivery of trained generalists who can use low-level telemedicine is the same as untrained generalists when treating non-critical patients. When we increase β to 1.3, then low-level telemedicine helps the trained generalists to provide treatment to non-critical patients at a 30% higher rate compared to untrained generalists. In other words, we can say that with telemedicine, the doctors can treat more patients and minimize the unmet healthcare demand."

In our instances, α varies from 0 to 1 with increments of 0.1, and β varies from 1 to 2 with increments of 0.1. From Table 5, we observe that in general, when we increase the value of α or β, the value of objective function decreases; hence, it improves. There a few instances (such as, β=1 and $0 \leq \alpha \leq 0.4$) where the objective function value is insensitive to

Table 4
Numerical results (θ = 0.7, $\alpha = 0.6$, $\beta = 1.3$). ω^* denotes the number of critical patients. ϕ ** denotes the number of non-critical patients.

	Data values		Decision variables						
Demand Points	ω^*	φ^{**}	y_j	$x_{j(ht)}$	$x_{j(lt)}$	$q_{j(s)}$	$q_{j(htg)}$	$q_{j(ltg)}$	$q_{j(g)}$
1	683	884	1	0	1	20	0	45	0
2	131	451	1	0	1	13	0	23	0
3	11	50	0	0	0	0	0	0	0
4	400	720	1	1	0	7	55	0	0
5	74	139	0	0	0	0	0	0	0
6	46	123	0	0	0	0	0	0	0
7	583	1641	1	0	1	58	0	76	0
8	246	723	1	0	1	25	0	36	0
9	86	259	0	0	0	0	0	0	0
Sum						$n_{(s)} = 123$	$n_{(htg)} = 55$	$n_{(ltg)} = 180$	$n_{(g)} = 0$
Optimal Solution		**78**							

Table 5
Objective values using parameters of the case study and varying the α and β

α \ β	1	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2
0	100.9	93.85	86.8	83.2	83.2	83.2	83.2	83.2	83.2	83.2	83.2
0.1	100.9	93.85	86.8	83.2	82.37	81.24	80.53	80.02	79.45	79.13	78.44
0.2	100.9	93.85	86.8	83.2	81.18	79.28	77.78	76.56	75.46	74.58	74.1
0.3	100.9	93.85	86.8	83.08	79.99	77.26	74.98	74.29	73.15	71.56	69.97
0.4	100.9	93.85	86.8	82.94	78.8	75.23	74.2	71.71	69.72	67.5	65.56
0.5	95.9	92.75	86.8	81.6	77.16	73.5	70.44	67.67	65.44	62.94	60.85
0.6	88.9	88.9	83.5	78.1	73.3	69.37	66.1	63.19	60.82	58.42	56.38
0.7	81.9	81.9	79.65	74.25	69.38	65.62	62.65	59.78	57.26	54.85	52.5
0.8	74.9	74.9	74.9	70.5	65.88	61.64	58.24	55.18	52.5	50.02	47.6
0.9	71.2	70	68.8	66.58	61.75	57.37	53.83	50.56	47.74	45.19	42.67
1	68.5	66.22	63.94	61.66	57.62	53.1	49.38	45.94	42.98	40.76	38.6

changes in α. This indicates that when the rate of service delivery of trained generalists who can use low-level telemedicine is the same as untrained generalists (β=1), low values in the rate of service delivery by trained generalists who can use high-level of telemedicine technology result in no reduction of unsatisfied demand ($0 \le \alpha \le 0.4$). This has an important implication for the management authorities that dedicating more resources to one area such as the training of generalists to use more advanced telemedicine technology, while simultaneously having trained generalists who can use low-level of telemedicine without a better performance than untrained generalists, will not improve the overall objective of meeting the unsatisfied demand.

From Table 5, we observe that as α approaches 1 and β approaches 2, with each increment, the proportion of improvement in the objective function value increases. For instance, when β=1.9, the improvement is 6.1% when α goes from 0.6 to 0.7; however, it jumps to 8.8% when α increases from 0.7 to 0.8. Moreover, an increase in α from 0.8 to 0.9 results in a 9.7% improvement in the objective function value.

7.2. Effect of triage-weighted factor, θ

It is a common practice in the event of a disaster to establish a triage system. Theoretically, the value of triage-weighted factor for the critical patients can vary between zero and one, i.e. $0 \le \theta \le 1$. Practically, the patients in critical condition are given higher priority than the patients in non-critical condition. A reasonable range for θ can be 0.6 to 0.8. Based on this reasoning, θ=0.7 in the base case scenario. From Figure 3, we can observe that the objective value gradually increases when we increment the value of θ from 0.5 to 0.7, and then it decreases when we increment the value of θ from 0.8 to 0.9. It is important to remember that in practice, one category of patients cannot be assigned all the weightage, by ignoring the other group.

In Table 6, we observe that regardless of the value of θ, we establish five THFs at the demand points 1, 2, 4, 7, and 8. The value of θ, however, impacts the decision of installing a high-level of telemedicine technology, low-level of telemedicine technology or no telemedicine at a THF.

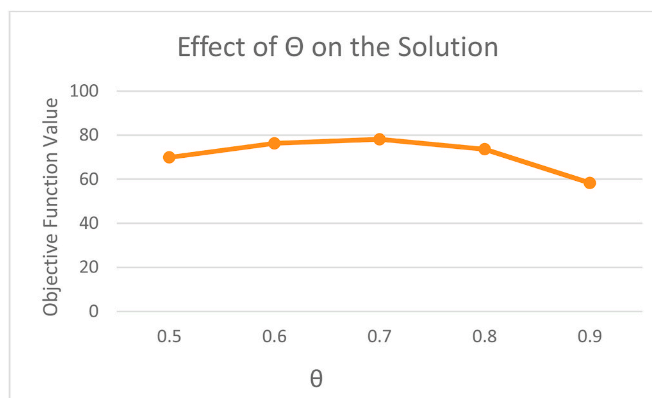

Fig. 3. Triage weighted factor and objective values.

When θ=0.6 and θ=0.7, we have one THF with high-level of telemedicine technology and the remaining four THFs are with low-level of telemedicine technology. When θ=0.8 and θ=0.9, a higher weight is assigned to the critical patients; therefore, we have two THFs with high-level of telemedicine technology and three with no telemedicine technology, as all of the budget available for telemedicine installation is allocated to $x_{j(ht)}$.

7.3. Effect of budget-related parameters, H, T and L

Recall that the three budget-related parameters H, T and L are defined as the available budget, respectively, for i) establishing THFs, ii) telemedicine training of doctors, and iii) telemedicine installation. Row 4 of Table 7 indicates the optimal solution of the base case scenario, where H=25000, T=10000, L=35000. The first section of Table 7 represents the effect of the changes in H on the objective value while keeping the other parameters constant. Similarly, the second and third

Table 6
Triage-weighted factor and types of THF.

Demand Points	y_j	θ = 0.6		θ = 0.7		θ = 0.8		θ = 0.9	
		$x_{j(ht)}$	$x_{j(lt)}$	$x_{j(ht)}$	$x_{j(lt)}$	$x_{j(ht)}$	$x_{j(lt)}$	$x_{j(ht)}$•	$x_{j(lt)}$
1	1	0	1	0	1	0	0	0	0
2	1	1	0	0	1	0	0	0	0
3	0	0	0	0	0	0	0	0	0
4	1	0	1	1	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0
7	1	0	1	0	1	1	0	1	0
8	1	0	1	0	1	1	0	1	0
9	0	0	0	0	0	0	0	0	0

Table 7
Budget related parameters and objective values.

H	T	L	Solution	H	T	L	Solution	H	T	L	Solution
10000	10000	35000	118.9	25000	*2500*	35000	91.9	25000	10000	*20000*	83.35
15000	10000	35000	81.46	25000	*5000*	35000	83.14	25000	10000	*25000*	81.46
20000	10000	35000	79.06	25000	*7500*	35000	80.38	25000	10000	*30000*	79.06
25000	**10000**	**35000**	**78.1**	**25000**	***10000***	**35000**	**78.1**	**25000**	**10000**	***35000***	**78.1**
30000	10000	35000	78.1	25000	*12500*	35000	77.11	25000	10000	*40000*	78.1
35000	10000	35000	78.1	25000	*15000*	35000	76.36	25000	10000	*45000*	78.1
40000	10000	35000	78.1	25000	*17500*	35000	76.36	25000	10000	*50000*	78.1

sections of the table illustrate the results for the changes in T and L, respectively. The value of H varies between 10000 and 40000, T between 2500 and 17500, and L between 20000 and 50000 as shown in their respective sections of Table 7. Intuitively, when we increase any of the three budgets, the objective function value should improve; i.e. decrease. However, we can see that in the first section of the table when we have H=25000, and in the third section when we have L=35000, any addition to these budgets do not result in the improvement of the objective value. This is because of the other constraints, such as the limited number of doctors. Even if we increase the budgets, we do not have enough health professionals to provide medical treatment to the victims of the earthquake. It is important to note that in order to meet the healthcare demand of the disaster victims, the management authorities should invest in the human resource, and not just increase the budgeting money for establishing the infrastructure.

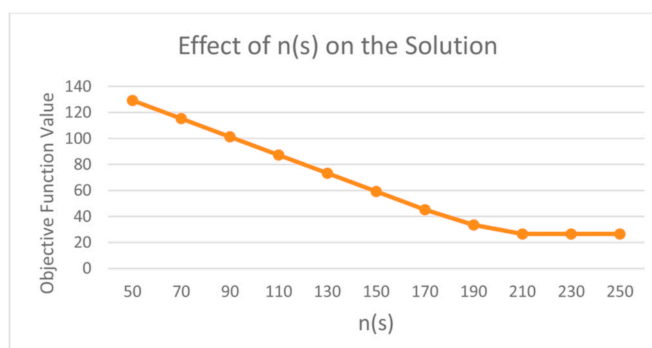

Fig. 4. Specialists and objective values.

7.4. Effect of the number of health professionals, $n_{(s)}$ and n

Keeping the parameters from the base case scenario constant, we vary the number of specialists, $n_{(s)}$, between 50 and 250. The results are presented in Figure 4. We start by 50 specialists and increase the number by 10 units until we reach the point when the optimal solution no longer improves. From Figure 4, we observe that the objective function value plateaus out after we have 210 specialists. Beyond this point, if we continue to add and assign more specialists to the THFs, while keeping the other parameters at the current level, the optimal solution will not improve. This is expected because we will not be able to open more THFs at the demand points because of cost and budget constraints.

Similarly, as we increase the number of generalists, n, by 10 units from 220 to 420 while keeping the other parameters constant, the optimal solution improves gradually as presented in Figure 5. After the value of 390, the objective function value does not improve. This inability to further reduce the unmet demand is due to the cost and

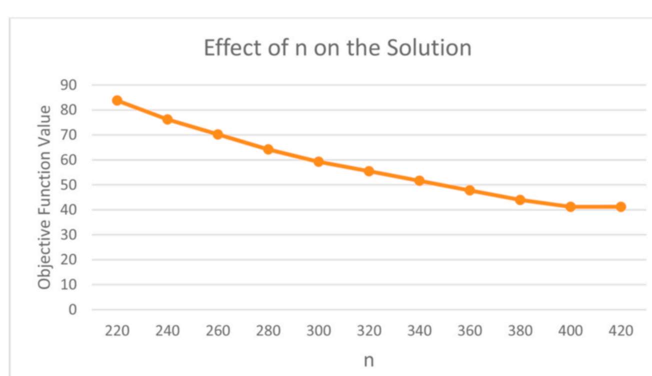

Fig. 5. Generalists and objective values.

budget-related constraints becoming binding, thereby nulling the benefit of increasing the number of generalists. From Figure 4 and Figure 5, it can be observed that the optimal solution is more sensitive to the changes in the number of specialists than the generalists. As evident from these two figures, the objective value improves at a slower rate by the increase in the number of generalists as compared to the specialists. A reason for this difference can be attributed to the higher triage-weighted factor assigned to the critical patients who are treated by the specialists.

7.5. Effect of cost parameter, c

Figure 6 shows that, as expected, with the increase in the cost of establishing a THF at a demand point 'c', the objective value increases and broadens the gap between the demand and supply of health professionals. An interesting insight that we gain by looking at the figure, is that the optimal solution is less sensitive to the changes in the parameter 'c' in the base case scenario when $n_{(s)}$=123 and n =235. As we increase the value of n from 235 to 435, by 100 units every time, the objective value increases more rapidly. When $n_{(s)}$=223 and n =235, the objective value becomes even more sensitive to the changes in the parameter c. This result reinforces our previous assertion about the sensitivity of the objective value to the changes in the number of specialists and critical patients. Additionally, it appears that the objective value stagnates when it reaches about 120 (to be exact, 118.9) in all the cases, but if 'c' is further increased the objective value will continue to get worse slowly until the cost of establishing a THF exceeds the available budget 'H' in which case there will not be any THFs; therefore, no demand will be satisfied.

8. A Two-Stage Stochastic Programming Framework

One of the assumptions in Section 4 is that the telemedicine training of generalists could be performed post-disaster and pre-deployment. However, there are situations where this may not be feasible. To this end, in this section, we present a two-stage stochastic programming framework, which encompasses a pre-disaster training of the generalists and a post-disaster location-allocation problem very similar to the one from Section 4. Figure 7 provides a visual representation of this process.

In this framework, the first stage (depicted by the decision node γ) represents the choice of number of generalists receiving a pre-disaster training in either high or low-level telemedicine technology. In this case, Constraint (2) from Section 4 (the telemedicine training budget) now becomes the only constraint in Stage 1. Each branch originating at γ represents a different combination of high and low-level trained generalists that satisfy this training constraint. It can be easily shown that this constraint should be binding (or "almost" binding since the integral decision variables might not always guarantee that the left and right-hand sides are equal) to maximize the treatment rate of doctors for the second stage. Therefore, the top branch, for example, would have the maximum number of generalists trained in high-level telemedicine technology (so, $n_{(htg)} = \left\lfloor \frac{T}{u_{(htg)}} \right\rfloor$ and $n_{(ltg)} = \left\lfloor \frac{T - n(htg).u_{(htg)}}{u_{(ltg)}} \right\rfloor$, where $n_{(htg)}$ and $n_{(ltg)}$ need to be rounded down to the nearest integers). The second

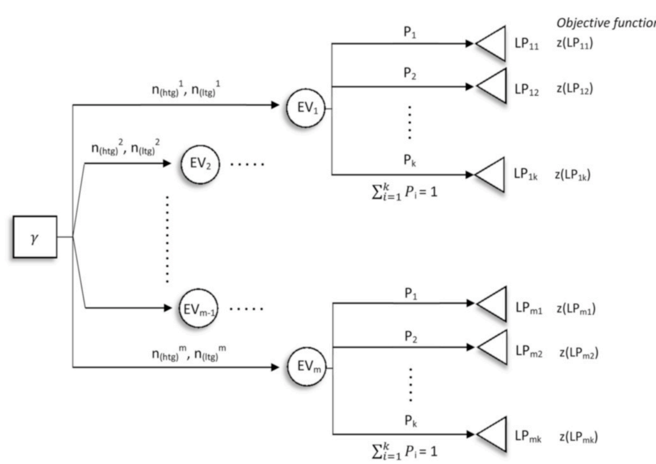

Fig. 7. A two-stage stochastic programming framework.

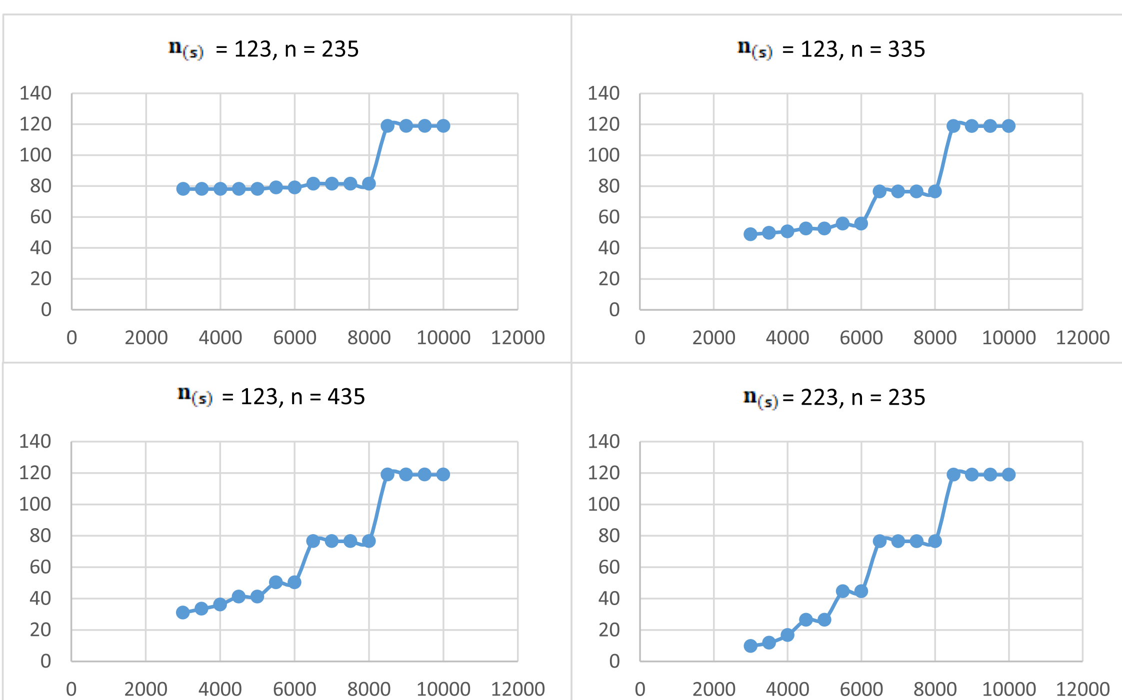

Fig. 6. Effect of 'c' on the objective value with varying levels of $n_{(s)}$ and n(x-axes represent 'c' and y-axes represent the objective function value).

branch would reduce $n_{(htg)}$ by 1 and add as many low-level trained generalists as the budget allows. We perform this procedure until the last combination where the number of high-level trained doctors is the smallest (perhaps even zero).

The second stage (depicted by the various circular chance nodes) is the discrete random event that represents the "k" number of disaster scenarios (Table 4 presents one example of such a scenario). Therefore, connected to each decision branch from Stage 1, there are "k" chance branches, each representing a disaster scenario with probability P_i. Of course, these probabilities, add up to 1. The magnitude and nature of the earthquake determines the profile of injuries, resulting in demand for the doctors. Each discrete demand scenario results in a location-allocation LP problem very much like the one described in Section 4. The major difference is that $n_{(htg)}$ and $n_{(ltg)}$ are now parameters, rather than decision variables, since their values were selected in Stage 1. This also implies that $n_{(g)}$ is a fixed number as well. Therefore, Constraints (2) and (3) would not be used in these problems. We can then solve each Stage 2 LP problem to find its optimal objective function value. This allows us to find the expected value of each decision branch and pick the optimal allocation of high and low-level trained generalists in Stage 1. Please refer to equations (18)–(26) for examples on how to calculate the expected value of three such branches.

First Branch:

$$n_{(htg)}{}^1 = \left\lfloor \frac{T}{u_{(htg)}} \right\rfloor \tag{18}$$

$$n_{(ltg)}{}^1 = \left\lfloor \frac{T - n_{(htg)}{}^1 . u_{(htg)}}{u_{(ltg)}} \right\rfloor \tag{19}$$

$$EV_1 = \sum_{i=1}^{k} z.(LP_{1i})\ P_i \tag{20}$$

Second Branch:

$$n_{(htg)}{}^2 = \left\lfloor \frac{T}{u_{(htg)}} \right\rfloor - 1 \tag{21}$$

$$n(ltg)^2 = \left\lfloor \frac{T - n_{(htg)}{}^2 . u_{(htg)}}{u_{(ltg)}} \right\rfloor \tag{22}$$

$$EV_2 = \sum_{i=1}^{k} z.(LP_{2i}).\ P_i \tag{23}$$

Last Branch:

$$n_{(htg)}{}^m = \left\lfloor \frac{T - n_{(ltg)}{}^m . u_{(ltg)}}{u_{(htg)}} \right\rfloor \tag{24}$$

$$n_{(ltg)}{}^m = \left\lfloor \frac{T}{u_{(ltg)}} \right\rfloor \tag{25}$$

$$EV_m = \sum_{i=1}^{k} z.(LP_{mi}).P_i \tag{26}$$

n equations (18) to (26), T is a parameter and represents the available bget for telemedicine training of the doctors. $n_{(htg)}$ is a pre-disaster decision variable, which determines the number of trained generalists who can use high-level of telemedicine technology. Similarly, $n_{(ltg)}$ determines the number of trained generalists who can use low-level of telemedicine technology. $u_{(htg)}$ and $u_{(ltg)}$ are parameters and represent the unit costs of training a doctor to use high-level telemedicine technology and low-level telemedicine technology respectively.

9. Conclusion

9.1. Main Contributions

In this research, we address the problem of optimally locating a THF, allocating health professionals to these facilities, and incorporating telemedicine into an earthquake response phase. We focus on significant earthquakes because they immensely impact people's lives. We review the relevant literature and develop an integer linear program to minimize the total weighted unsatisfied healthcare demand. The proposed model provides an approach to optimize the selection and establishment of temporary health facilities (THFs) in an earthquake-affected area, and to allocate healthcare professionals, such as doctors, to the THFs who can provide in-person and virtual care to the disaster victims.

We apply our model to a case study, using real data from the 2005 Kashmir Earthquake that occurred in the northern parts of Pakistan, which include the Pakistan-administered portion of the Kashmir region (Azad Jammu and Kashmir - AJK) and the Khyber Pukhtunwa (KPK) province. Given the lack of planning and the bottlenecks encountered by the earthquake management organization during the relief phase, our solution, if implemented, would be of significant benefit. This implies that the use of telemedicine in an earthquake relief and rescue phase can result in accelerated healthcare provision to the disaster victims and shrink the gap between the supply and demand of health professionals in the field.

We contribute to humanitarian logistics literature by proposing a computationally efficient and a linear model to analyze a temporary healthcare facility-location problem post-disaster, specifically after an earthquake. The model incorporates telemedicine in the disaster response phase and provides an optimal solution for minimizing unmet healthcare demand by allocating health professionals to the demand points. Our analysis shows that such a response mechanism may provide substantial support to humanitarian response operations. In order to introduce variability and uncertainty to the model, we propose an additional two-stage stochastic programming framework, which encompasses a pre-disaster training of the generalists and a post-disaster location-allocation problem.

9.2. Practical Implications

Recently, establishing temporary response facilities, as a part of emergency activities, has gained increasing attention from academics and practitioners alike. A significant earthquake can extensively damage the local healthcare facilities or may make them inaccessible to the affected population. Even when the infrastructure withstands the disaster, various forms of disaster-related injuries/diseases may arise, requiring medical specialists who are not available in the smaller towns and villages of the affected region. A major obstacle to the efficacy of emergency response is the unexpected surge in injuries and overwhelming demand for medical treatment that local healthcare units may not be able to provide. In such cases, establishing temporary health facilities and using telemedicine can enable the healthcare personnel to handle more patients than conventional healthcare systems would typically allow, by using electronic equipment and accessing specialists in well-equipped, out-of-range hospitals [42].

During the relief phase, due to the limited availability of information, a comprehensive but straightforward model, as proposed in this paper, can greatly help the emergency management organization in minimizing the unmet healthcare demand. In the sensitivity analysis section, we alter the model parameters and test some what-if scenarios, using the case study as the base case scenario. After inspecting the output, we observe that in general, when we increase the value of the parameters α, β, H, T, L, $n_{(s)}$ and n , the objective value decreases, hence it improves. However, we can increase one parameter just enough, after which the objective value becomes insensitive to the changes in the parameter. At this point, to further improve the solution, we need to increase the other parameters as well. This finding has an important implication for the earthquake management authorities that dedicating more resources to one area, while simultaneously keeping the other parameters the same, may not always improve the overall objective of reducing the unsatisfied healthcare demand. The proposed model is computationally efficient and tractable, and the result of this study can be useful to a response team that is responsible for the selection of THFs and allocation of resources in a low-income country with limited resources.

9.3. Limitations and Future Research Directions

Earlier, we stated that the purpose of this optimization model is to assist the relief phase of a significant earthquake. Since an exact solution can be obtained in less than twenty seconds, we can assume that an earthquake management organization has enough time to run the model multiple times and obtain the results for a sufficiently large number of scenarios. The main model described in Section 4 contains only deterministic parameters, where the number of injured people is known. However, in the case of a natural disaster, the number of affected people is not readily available. To compensate for this limitation, we proposed a two-stage stochastic programming framework in Section 8.

Another research idea to incorporate uncertainty and variability in the model is to use tools such as Queuing Theory and Simulation. Finally, the proposed model and framework are quantitative in nature and do not consider subjective attributes in evaluating THF location alternatives. Future work can focus on qualitative factors, using techniques such as fuzzy multi-attribute decision making.

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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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