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Disaster Assessment and Mitigation Planning: A Humanitarian Logistics Based Approach

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ABSTRACT

This paper proposes a mathematical modeling-based approach for assessing disaster effects and selecting suitable mitigation alternatives to provide humanitarian relief (HR) supplies, shelter, rescue services, and long-term services after a disaster event. Mitigation steps, such as arrangement of shelter and providing HR items (food, water, medicine, etc.) are the immediate requirements after a disaster. Since governments and non-governmental organizations (NGOs) providing humanitarian aid need to know the requirements of relief supplies and resources for collecting relief supplies, organizing and initiating mitigation steps, a quick assessment of the requirements is the precondition for effective disaster management. Based on satellite images from weather forecasting channels, an area/dimension of the disaster-affected zones and the extent of the overall damage may often be obtained. The proposed approach then estimates the requirements for HR supplies, supporting resources, and rescue services using the census and other government data. It then determines reliable transportation routes, optimum collection and distribution centers, alternatives for resource support, rescue services, and long-term help needed for the disaster-affected zones. A numerical example illustrates the applicability of the model in disaster mitigation planning.

Keywords: Disaster Assessment, Humanitarian Relief Operations, Disaster Mitigation Alternatives, Mixed-Integer Programming

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1. INTRODUCTION

The increasing frequencies of natural disaster occurrences have made humanitarian logistics and disaster mitigation planning an important research area. Disaster occurrences and their impact on resources and human lives have been widely covered in the literature, news media, and publications from international organizations (ABC News, 2010; De Marchi, 2007; IFRC, 2011; Lees, 1996; Loayza *et al.*, 2012; Magnone, 2012; Rodriguez *et al.*, 2012; United Nations, 2008). Disaster management includes assessment of the vulnerabilities of a disaster-prone zone for planning preventive measures or mitigation preparation (Hochrainer and Mechler, 2011; Wei *et al.*, 2004), assessment of the needs after the disaster (Chen *et al.*, 2012; Leaning, 2008; Lillibridge *et al.*, 1993), identification of logistical factors for mitigation planning (Nivolianitou and Synodinou, 2011), and coping with the disaster event for relief and rehabilitation of the affected population (Pomeroy *et al.*, 2006). Other studies have focused on relief allocation strategies to ensure that the affected populations receive relief, especially in developing countries (Morris and Wodon, 2003).

Past disaster events have highlighted the requirements of emergency rescue services, emergency medical needs, shelter and other resource supports in addition to relief supplies (e.g., food, medicine, and potable water) in the affected zones (Owens *et al.*, 2005; van der Velden *et al.*, 2012; Watt, 1977). It may be noted here that the emergency rescue services, medical needs, and shelters are to be provided in the immediate aftermath of the disaster. To ensure a timely response to the needs for emergency services (rescue assistance, medical supports, and shelter) and humanitarian relief (HR) supplies (food, medicine, potable water), the supporting organizations (government agencies, non-governmental organizations [NGOs], and private entities) need an assessment of the disaster effects just after the event, which constitutes the basis for procuring and organizing relief supplies and resources to be included in any mitigation plan. In the context of assessment, it may be noted that the effects of a disaster event change dynamically as time passes. In some cases (e.g., floods, droughts, volcanic eruptions, nuclear disasters) the effects of the disaster may continue for days or even weeks, prompting the authorities to rely on satellite images (broadcast by news media, government agencies, etc.) to conduct the assessment and to dynamically update it as time passes. This information combined with governmental data (such as census information, local economic data, etc.) may be used to arrive at an acceptable quality, first-hand assessment that may be refined later.

It is apparent that the service-providing organizations including government agencies will need information on the availability and reliability of transportation networks, and suitable distribution centers to be assigned to the affected zones to provide relief work and emergency services. Often supply centers that procure relief items and organize support activities may be spread over the country. Thus, the decision needs to be made to choose suitable supply and distribution centers, transportation modes, and the quantities to be sent to each affected zone considering the dynamically changing disaster situation and the transportation network condition.

An affected zone also requires emergency resource supports in terms of medical aid, shelter, and rescue services. Supporting organizations need to select suitable options in terms of cost, practical feasibility, and availability of emergency services to provide quick responses for providing such resource supports in addition to the amount of relief items.

Based on the extent of the damage caused by a disaster, there may be affected populations in select zones that would not be able to get back to their homes for a few months. In such situations, there is a need for extended-time rehabilitation help in the form of temporary schools for children, repairing or rebuilding the damaged homes, and other supports in order to get the affected population to resume their economic activities.

In view of the multiplicity of the assessment variables, response requirements, and the available options, a structured, mathematical modeling-based approach is suggested that would aid the supporting organizations in coming up with timely and appropriate decisions. There are a limited number of studies that comprehensively address disaster mitigation plans based on the assessment of appropriate requirements discussed above. This study is an attempt to bring into the picture an assessment and mitigation plan that recognizes the foreseeable effects of a disaster.

The remainder of the paper is organized in the following way. The next section includes literature survey. Section 3 develops the mathematical model and outlines the problem statement, assumptions, and the schematic network view of the problem, as well as the model and its description. Section 4 illustrates the model application using a numerical example, and Section 5 closes with some observations and conclusions.

2. LITERATURE SURVEY

In this section we present a review of the literature on: 1) emergency relief requirements, distribution and transportation networks; 2) rescue services in the event of a natural disaster; 3) resource requirements when disaster hits; 4) rehabilitation or long-term support requirements; and 5) planning and management of mitigation measures.

2.1 Emergency Relief Requirements, Distribution and Transportation Network

The literature on humanitarian emergency logistics planning is mostly focused on distribution and transportation of relief supplies. An overview of the issues involved in the transportation and routing of relief supplies may be found in the review study by de la Torre *et al*. (2012). Liberatore *et al.* (2012) proposed an emergency goods distribution model and illustrated its application to the Haiti earthquake disaster. In addition to addressing the optimum distribution network selection, the paper addressed a recovery plan for the damaged connection arcs of the network using predefined 0/1 reliability levels and set amounts of construction cost. Berkoune *et al.* (2012) proposed a model for transportation and delivery of relief items from a set of distribution centers to demand nodes. The model also determines the optimum number of trips and vehicle types. Lin *et al.* (2011) proposed a multi-item, multi-vehicle, and multi-period integer programming model for the delivery of emergency supplies after a disaster considering the unlimited capacity of a single supply depot to satisfy multiple demand nodes.

2.2 Rescue Services in the Event of Natural Disasters

Rescue services and the relevant planning-related problems are not well covered in the disaster management literature. Sheu (2010) proposed a model for estimating and dynamically updating the number of persons trapped, fatalities involved and the rescue relief requirements in earthquake-like disasters. Fiedrich *et al.* (2000) proposed a similar dynamic model for optimal assignment of available resources for rescuing the earthquake-trapped population with the objective of minimizing fatalities. Auf der Heide (2006) recommended evidence-based rescue services planning based on the investigation of the data collected on-site just after the disaster.

2.3 Resource Requirements When Disaster Hits

Most of the literature on humanitarian logistics studied resource supports as a part of the general relief operations instead of considering it as a separate topic. In 1998 the U.S. government developed the National Disaster Medical System as an asset of the Federal Emergency Management Agency to provide state-of-the-art medical care to U.S. citizens living abroad, and to assist host countries, in the event of a disaster. It deploys with medical supplies, pharmaceuticals, surgical equipment, and a Deployable Rapid Assembly Shelter/Surgical Hospital (Owens *et al*., 2005). Such resources involve large investments and are usually out of reach for developing or under-developed countries. To reduce fatalities in earthquake disaster areas, Liu *et al.* (2011) proposed site selection approaches to build emergency shelters outside the earthquake vulnerable areas. This study offers an example of readiness planning for future disaster events. In a similar vein, Chen *et al.* (2011) proposed a disaster response framework and model for providing emergency civil engineering construction equipment support to disaster-hit urban areas. The proposed framework and integrated model includes geographic information system (GIS)-based information collection facilities that aid in allocating resources based on the requirements. Helicopters are an example of the emergency service resources that are used for population evacuation, transportation to shelters and hospitals, and for rescue operations in the event of a disaster. Considering these factors, Fenn *et al.* (1999) studied the assessment of preparedness planning for the U.S. Helicopter Emergency Medical Services in response to disasters.

2.4 Rehabilitation or Long-Term Support Requirements

Extended-time supports or rehabilitation supports are provided by the United Nations organizations (e.g., General Assembly, 2012), regional support centers (e.g., CONSRN, 2005), similar international organizations, and national governments. Pomeroy *et al.* (2006) studied past natural disasters including the Asian tsunami and proposed principles for rehabilitating coastal livelihoods. Literature also covers medical rehabilitation studies. Bathala (2005) conducted a case study at a walk-in clinic at a refugee relief camp in Krabi, Thailand. Based on the treatment and evaluation of more than 500 patients injured in the 2004 tsunami, the author reported that rehabilitation medicine was essential in the natural disaster relief work. Hashemi and Alesheikh (2011) proposed a model for assessment, mitigation and rehabilitation of building structures, roads, and highway networks damaged by earthquakes.

2.5 Planning and Management of Mitigation Measures

Using an empirical study based on the emergency response teams in Greece, Nivolianitou and Synodinou (2011) identified operational and logistical factors that facilitate emergency management of natural disasters and accidents. Examples of the factors identified include mobilization of emergency groups, early reaction time, information technology, and competence of the response team. Humanitarian logistics involves several parties including international donor agencies, local donors, NGOs and government agencies in addition to the entities involved in transportation, warehousing, and information services. Balcik *et al.* (2010) studied the coordination practices and challenges in relief works in disaster-affected zones. Based on their analysis and comparing the current situation with the commercial supply chains, the authors concluded that the current practices of collaborative procurement and third-party warehousing had been conducive to relief environment. Optimization models have been used by several researchers in disaster management and emergency logistics planning (e.g., see Caunhye *et al.*, 2012). To obtain cost effective and real time solutions for mitigating disaster events, Altay and Green III (2006) suggested OR/MS-based disaster operations management approach as the most suitable method considering the randomness of the disaster impacts in addition to uniqueness of the demand dynamics.

The literature review reveals that the crucial disaster management factors are disaster assessment and relief operations to provide rescue services; transportation and distribution of HR items; providing resource support in terms of shelter and medical services; and planning for extended-time rehabilitations in select disaster cases. The literature also reveals that the disaster events in most cases need quick mitigation responses in terms of all the factors, not on just one or two. Table 1 shows the specific areas addressed and the methodologies used towards disaster mitigation by select literature.

It is apparent that there is no comprehensive disaster management approach in the literature that includes suitable criteria on the assessment of requirements and mitigation plan for HR items (food, water, and medicine),

Table 1. Disaster mitigation approaches studied in select literature

Addressed area	Proposed mitigation	Methodology	Reference
(a), (b)	Risk pooling among cities, infrastructure and liquidity support	Investigation of resources in Asian cities and past risk events	Hochrainer and Mechler (2011)
(a), (b), (e)	Deployment and planning of resources for relief operation	Transportation model	Berkoune *et al*. (2012)
(a), (e)	Coordination of relief chains in pre and post disaster relief operation	Study of relief and commercial supply chain operation	Balcik *et al.* (2010)
(e)	OR/MS approach for readiness, response, and disaster recovery	Review study	Altay and Green (2006)
(e)	Optimal assignment of available resources to reduce fatalities	Dynamic optimization model	Fiedrich *et al.* (2000)
(b)	Emergency health care resources deployment	Experience based response recommendation and planning	Owens *et al.* (2005)
(b), (e)	Evacuation of people and resources from disaster hit urban areas	Model based risk assessment evacuation planning	Chen *et al.* (2012)
(c)	Contribution of armed services in rescue, evacuation and others	Review of relevant lectures	Watt (1977)
(a), (b), (e)	Earthquake loss estimation for mitigation and aversion planning	Pre- and post-earthquake disaster assessment model	Hashemi and Alsheikh (2011)
(b), (c), (e)	Identification of factors for effective emergency management and intervention	Study of policies/protocols, and interviewing stakeholders in risk and emergencies	Nivolianitou and Synodinou (2011)
(a), (d), (e)	Distribution of relief items and quick recovery from disaster effects	Model for recovery of damaged distribution networks	Liberatore *et al.* (2011)
(a), (b), (e)	Data based DSS supports damage assessment and management	Decision support system (DSS) to disaster management	Rodriguez *et al.* (2012)
(b), (d), (e)	Allocation of construction equipment for disaster response operation	A decision model	Chen *et al.* (2011)
(a), (b), (d)	For designing interventions to long- and short-term vulnerabilities	Study of past lessons to draw recommendations	Pomeroy *et al.* (2006)

(a): emergency relief requirements, distribution and transportation network, includes risk assessment, (b): resources requirements (aversion and or mitigation), (c): rescue services, (d): rehabilitation, long and short term support, (e): planning and management of mitigation measures. OR/MS: operations research/management science.

Table 2. Humanitarian logistics planning framework

Assessment of disaster effect	Estimation of relief items
Basis information - Satellite images of affected areas from weather channels - Area of the affected zone from state agency data - Data on population, housing, roads, building, and resources from state and census information	- Humanitarian relief (HR) items: Food, potable water, clothes, first aid medicine **Emergency resources** - Medical aid item: mobile/temporary hospitals, ambulances, physicians, nurses, and medicine. - Shelter: Temporary shelters (tents, building materials), possible relocation shelter to nearby cities, DCs - Rescue services: Rescue equipment, transportation, helicopters, trained personnel - Utility resources: Temporary power, water and sewerage facilities
Logistics data for mitigation planning	**Mitigation planning**
- Transportation network to affected zone for each mode with reliability - Distribution centers (DC): Possible nearby city centers, and other facilities - Supply centers (SC): Locations for government agencies, non-governmental organizations, and other humanitarian organizations	- Transportation planning: HR items from SC to DCs - Distribution planning: HR items from DCs to affected demand zones - Rescue services: Allocation of equipment, teams from DCs to affected demand zones - Shelter: allocation of temporary shelters, planning on relocation options - Medical aid: allocation of teams, temporary facilities, relocation option to nearby city hospitals - Extended time support: allocation of teams and resources in DCs to affected demand zones.

resources for emergency services (rescue, shelter, medical) and extended-time support or rehabilitation plan for disaster-affected population. This study is an attempt to fill that gap

3. DISASTER ASSESSMENT AND MITIGATION MODEL

This section includes the problem statement, a humanitarian logistics planning framework for disaster mitigation, and the mathematical model formulation.

3.1 Problem Statement

We assume that a set of areas N^d (demand nodes, or zones) of a country is struck by flood or cyclone, affecting a set of resources B including homes, hospitals, schools, power supply, and municipal water supply lines (either due to flood water flows, or the river overflow in case of the cyclone). The communication networks connecting the demand nodes with the rest of the country are also affected. Let N^c be the set of supply nodes where disaster relief agencies (governmental, NGOs, etc.) are located, and where they collect HR items, organize temporary shelters or shelter construction materials, and other resources from donor agencies (foreign or local) for disaster mitigation activities. Quick assessment of the relief and resource requirements will enable both the government agencies and the NGOs to take timely steps for collecting the required amounts of relief materials. The objectives of the study are to assess the disaster effect, estimate requirements for relief supplies, resources, and support services; evaluate the communication networks in the affected areas; and develop a mitigation plan for sending relief items from optimally-located supply nodes, and for providing resource supports considering various alternatives. The problem statement also includes the following assumptions:

1) Sufficient relief items and resources (for emergency support, rescue services, and extended time services) have been procured from the donor services and markets. As such there will be no shortages of the relief items and resources for supplying to the demand nodes.
2) Cost of relief items, resources, transportation, repair, restoration, and services (rescue, extended-time support, and emergency support and medical treatment) are known and will not change during the entire mitigation time horizon.
3) Sufficient and required number of trained service personnel, transports, equipment, and other resources are organized by the relief team.
4) Position of distribution nodes, transit nodes, transportation routes, and demand nodes have been decided based on maps and GIS data.
5) The monitoring cells have the required expertise and resources to track the routes, weather condition, and disaster effects at the demand nodes.
6) Data on affected population, per person HR and other relief requirements are available.

3.2 The Model Formulation

In this sub-section we first define the notations and then present the mathematical model.

3.2.1 Notations

Indices

B the set of immediately needed resources, $b \in B$

G the set of extended-time rehabilitation resources/supports for long-term disaster mitigation, $g \in G$

E the set of emergency rescue services, $e \in E$ (needed for rescuing people trapped in flooded areas, under debris in earthquake situations, etc.); e = 1, trained rescue teams; e = 2, motorized boats/helicopters, ambulances; e = 3, others

I the set of HR items, such as drinking water, food, medicine, $i \in I$

M the set of transportation modes (highways, railways, water ways, mixed modes, air) for connecting supply nodes to demand nodes, $m \in M$

N a set of nodes (demand zones, destinations/supply centers, indexed by $n \in N$ and $n' \in N$

N^d a set of demand nodes, $n \in N^d$, $n' \in N^d$

N^c a set of supply nodes, $n \in N^c$, $n' \in N^c$

N^w a set of distribution center (DC) nodes, $n \in N^w$, $n' \in N^w$

N^t a set of transit nodes along the communication network $n \in N^t$, $n' \in N^t$
(N^d, N^c, N^t, and N^w are the partitions of N)

O set of options, $o \in O$ for organizing immediate resources, for example, relevant to shelter; option o = 1 construction of temporary shelter (tents, big sheds, etc.); o = 2 moving the affected population to a safe, already built shelter (outside the vulnerable area, perhaps in a different state or city) using ships, airways, and other transports as feasible. Similarly for hospitals, option o = 1 means taking mobile hospital vans, wagons, and ships to the affected area; o = 2 means moving the affected population to hospitals in a nearby state or city using suitable transportation.

T time periods; each period t is 1 day, $t \in T$

Parameters

BN : a large positive number

$CA^m_{nn't}$: cost of maintaining an alternative route from $n \in N$ to $n' \in N$ for transportation mode m in period t

CAM^m_i : capacity of transportation mode m to carry HR item i

CAW_{int} : capacity of DC node $n \in N^w$ for HR item i in period t

$CD_{nn'}$: per-unit cost of distributing HR items from DC node $n \in N^w$ to demand node $n \in N^d$

CE_e : per-family cost of emergency rescue service e

$CH^{m}_{nn't}$: cost of maintaining an existing route from $n \in N$ to $n' \in N$ for transportation mode m in period t
CP_{it} : per-unit cost of purchasing HR items i in period t
$CPL^{m}_{nn't}$: cost of selecting air transportation mode m from $n \in N$ to $n' \in N$ in period t
CPS_{en} : capacity of demand node n to provide a unit of emergency rescue service e
CPX_{gn} : capacity of DC node $n \in N^w$ to provide extended-time rehabilitation resource g to a demand node
CR_{bot} : cost of providing immediate resource b under option o in period t
CS_{in} : capacity of the supply node $n \in N^c$ to accommodate HR item i
$CT^{m}_{nn'}$: per-unit cost of transporting HR items using transportation mode m from node $n \in N$ to $n' \in N$
CX_g : per-family cost of extended-time rehabilitation resource g
dx_n; des_{en}; del_{bn}: 0/1 parameters set by the central disaster monitoring cell to decide on the applicability of extended-time rehabilitation resources, rescue services and immediate resource requirements, respectively, at demand node $n \in N^d$
EQ_e : equivalent number of families that rescue service e can accommodate
ER_{ent} : estimated number of families that need emergency rescue service e at demand node $n \in N^d$ in period t based on media reports
ESX_{gn} : estimated number of families that need extended-time rehabilitation resource g (e.g., schools, medical support, shelters) at demand node $n \in N^d$
FB_{bno} : fixed cost of option o to provide immediate resource b at demand node $n \in N^d$
FES_{en} : fixed cost of providing emergency rescue service e from DC node $n \in N^w$
FK_n : fixed cost of opening transit node $n \in N^t$
FM_m : fixed cost of using transportation mode m
FN_n : fixed cost of opening supply node $n \in N^c$
FS_n : average family size at demand node $n \in N^d$ based on census data
FW_n : fixed cost of opening DC node $n \in N^w$
FX_{gn} : fixed cost of providing extended-time rehabilitation resource g from DC node $n \in N^w$
P_n : population size at demand node $n \in N^d$ based on area map and census data
PER_{en} : percentage of families that need emergency rescue service e at demand node $n \in N^d$ based on media/satellite scan-based reports on extent of damage
PR_{bn} : percentage of families that need resource b at demand node $n \in N^d$ based on media/satellite scan-based reports on the extent of damage
PXR_{gn} : estimated percentage of families that need extended time rehabilitation resource g at demand node $n \in N^d$ based on media/satellite scan-based reports on the extent of damage
R_{bnt} : estimated number of families that need immediate resource b at demand node $n \in N^d$ according to inspection/survey in period t
$RA^{m}_{nn't}$: a 0/1 parameter indicating the reliability status of transportation mode m on the alternative route from n to n' in period t as set by the monitoring cell
$RO^{m}_{nn't}$: a 0/1 parameter indicating the reliability status of transportation mode m on the existing route from n to n' in period t as set by the monitoring cell
$RPL^{m}_{nn't}$: a 0/1 parameter indicating the reliability status of air transportation mode m from n to n' in period t, as set by the monitoring cell
S_t : a safety index set by roads and transport authorities indicating the loading level of the transport (e.g., 90%, 80%, etc.) based on the severity of the disaster
TSU_{it} : total requirements of HR item i in period t
U_{in} : estimated per-family requirements of HR item i at demand node $n \in N^d$

Variables

$a_{nn'}$ = 1 if DC node $n \in N^w$ is assigned to demand node $n' \in N^d$; 0, otherwise
c_m = 1 if transportation mode m is selected; 0, otherwise
dxr_n = 1 if DC node $n \in N^w$ is operating to provide extended-time rehabilitation recourses; 0, otherwise
$ex_{gnn'}$: units of extended-time rehabilitation resource g supplied to demand node $n \in N^d$ from DC node $n' \in N^w$
$f^{m}_{inn't}$: quantity of HR item i moving along the route $n \in N$ to $n' \in N$ using transportation mode m in period t
h_n = 1 if DC node $n \in N^w$ is open; 0, otherwise
hes_n = 1 if DC node $n \in N^w$ is operating to provide rescue services; 0, otherwise
k_n = 1 if transit node $n \in N^t$ is open; 0, otherwise
$l_{nn'}$ = 1 if demand node $n' \in N^d$ is supplied extended-time resource b from DC node $n \in N^w$; 0 otherwise
mr_{bnot} : requirements of immediate resource b at demand node $n \in N^d$ under option o in period t
q_{int} : estimated requirements of HR item i in period t at demand node $n \in N^d$
$rla^{m}_{nn't}$ = 1 if the alternative route from $n \in N$ to $n' \in N$ is deemed reliable in period t using transportation mode m; 0, otherwise
$rl^{m}_{nn't}$ = 1 if the existing route from $n \in N$ to $n' \in N$ is deemed reliable in period t using transportation mode m; 0, otherwise
$rpl^{m}_{nn't}$ = 1 if existing and alternative routes for other modes are unavailable and air transportation mode m from $n \in N$ to $n' \in N$ is selected in pe-

riod t; 0, otherwise

$s_{enn't}$: units of emergency rescue service e provided at demand node $n \in N^d$ from DC node $n' \in N^w$ in period t

su_{int} : supply of HR item i at supply node $n \in N^c$, collected/received from outside, in period t

u_{bno} = 1 if option o is chosen for resource requirement b at demand node $n \in N^d$; 0, otherwise

v_n = 1 if supply node $n \in N^c$ is open; 0, otherwise

$w_{n'n}$ = 1 if emergency rescue service is provided at demand node $n \in N^d$ from DC node $n' \in N^w$; 0, otherwise

$y_{inn't}$: quantity of HR item i to be distributed from DC node $n \in N^w$ to demand node $n' \in N^d$ in period t

The Mathematical Model

The objective function is to *minimize* the *Total cost*, where:

$$Total\ cost = CHR+CTH+CMHR+CIR+CRS+CXT \quad (1)$$

The cost items for Eq. (1) are described below in Eq. (1.1) to (1.6):

$$CHR = \sum_{i\in I}\sum_{t\in T} CP_{it} \sum_{n\in N^w}\sum_{n'\in N^d} y_{inn't} + \sum_{n\in N^c} v_n FN_n \quad (1.1)$$

Eq. (1.1) computes *CHR,* the procurement and fixed cost of HR items.

$$CTH = \sum_{m\in M}\sum_{n\in N}\sum_{\substack{n,\in N\\ n\neq n'\\ n'>n}} CT^m_{nn'}\sum_{i\in I}\sum_{t\in T} f^m_{inn't} + \sum_{m\in M} c_m FM_m + \sum_{n\in N^t} k_n FK_n \quad (1.2)$$
$$+\sum_{n\in N^w}\sum_{n'\in N^d} CD_{nn'}\sum_{i\in I}\sum_{t\in T} y_{inn't} + \sum_{n\in N^w} h_n FW_n$$

Eq. (1.2) computes *CTH*, the cost of transporting HR items from supply nodes to DC nodes and distributing them to demand nodes, the fixed cost of keeping the distribution nodes and transit nodes open, and the fixed cost of selecting a transportation mode.

$$CMHR = \sum_{n\in N}\sum_{\substack{n'\in N\\ n'\neq n\\ n'>n}}\sum_{m\in M}\sum_{t\in T} rla^m_{nn't}CA^m_{nn't} + \sum_{n\in N}\sum_{\substack{n'\in N\\ n'\neq n\\ n'>n}}\sum_{m\in M}\sum_{t\in T} rl^m_{nn't}CH^m_{nn't} \quad (1.3)$$
$$+\sum_{n\in N}\sum_{\substack{n'\in N\\ n'\neq n\\ n'>n}}\sum_{m\in M}\sum_{t\in T} rpl^m_{nn't}CPL^m_{nn't}$$

Eq. (1.3) computes *CMHR*, the cost of maintaining the roads, highways, waterways, and airways in reliable conditions for the transportation modes used to send HR items to demand nodes.

$$CRR = \sum_{b\in B}\sum_{n\in N^d}\sum_{o\in O} u_{bno}FB_{bno} + \sum_{b\in B}\sum_{n\in N^d}\sum_{o\in O}\sum_{t\in T} mr_{bnot}CR_{bot} \quad (1.4)$$

Eq. (1.4) computes *CRR*, the cost of providing immediately-required resources considering the fixed cost of selecting the options and the overall cost of providing the resources under that option.

$$CRS = \sum_{e\in E} CE_e \sum_{n\in N^w}\sum_{n'\in N^d}\sum_{t\in T} s_{enn't} + \sum_{e\in E}\sum_{n\in N^w} hes_n FES_{en} \quad (1.5)$$

Eq. (1.5) computes *CRS*, the cost of providing emergency rescue services from a DC node to the demand node, and the fixed cost of providing the service at the DC node.

$$CXT = \sum_{g\in G} CX_g \sum_{n\in N^w}\sum_{n\in N^d} ex_{gnn'} + \sum_{n\in N^w} dxr_n FX_n \quad (1.6)$$

Eq. (1.6) computes *CXT*, the cost of providing extended-time rehabilitation resources from a DC node to a demand node and the fixed cost of providing the service at the DC node.

The constraints are as follows.

$$TSU_{it} = \sum_{n\in N^d} [\frac{P_n}{FS_n} U_{in}] \qquad \forall i \in I,\ t \quad (2)$$

Constraint (2) accumulates the total amounts of the HR item requirements in each period at all the demand nodes.

$$\sum_{n\in N^w} y_{inn't} \le q_{in't} \qquad \forall i,\ n' \in N^d,\ t \quad (3)$$

Constraint (3) balances the HR item shipments from DC nodes against the requirements at the demand nodes.

$$y_{inn't} \le a_{nn'} q_{in't} \quad \forall i,\ n \in N^w;\ n' \in N^d,\ t \quad (4)$$

The above constraint assigns DC nodes to demand nodes to address the requirements effectively.

$$\sum_{n'\in N^d} y_{inn't} \le h_n CAW_{\text{int}} \qquad \forall i,\ n \in N^w,\ t \quad (5)$$

Constraint (5) limits the shipments of an HR item from a DC node based on its capacity.

$$a_{nn'} \le h_n \qquad \forall n \in N^w,\ n' \in N^d \quad (6)$$

Constraint (6) ensures that a DC node is open before it is assigned to a demand node.

$$\sum_{m\in M}\sum_{n\in N} f^m_{inn't} = \sum_{n\in N^d} y_{in'nt} \qquad \forall i,\ n' \in N^w,\ t \quad (7)$$

Constraint (7) balances the flow of HR items to and from DC nodes.

$$f^m_{inn't} \le c_m CAM^m_i S_t \quad \forall i,\ n \in N,\ n' \in N,\ t,\ m \tag{8}$$

Constraint (8) limits the flow through a route based on the capacity of the transport mode selected.

$$su_{int} \le v_n CS_{in} \quad \forall i, n \in N^c,\ t \tag{9}$$

Constraint (9) limits the shipments of HR items from a supply node based on its capacity to store the items.

$$\sum_{n \in N^c} su_{int} = TSU_{it} \quad \forall i,\ t \tag{10}$$

Constraint (10) balances the total shipments of an HR item out of all the supply nodes in a period against the total requirements of that item in the same period.

$$su_{int} + \sum_{\substack{n' \in N \\ n' \ne n}} \sum_{m \in M} f^m_{in'nt} = \sum_{\substack{n'' \in N \\ n'' \ne n}} \sum_{m \in M} f^m_{inn''t} \quad \forall i,\ n \in N^c,\ t \tag{11}$$

Constraint (11) is a balance equation that keeps track of all the flows into and out of a supply node.

$$\sum_{\substack{n' \in N \\ n' \ne n}} f^m_{in'nt} = \sum_{\substack{n'' \in N \\ n'' \ne n}} f^m_{inn''t} \quad \forall i, n \in N^t,\ t \tag{12}$$

Eq. (12) balances the inflow with the outflow for the transit node that does not have an inflow from outside sources.

$$F^m_{inn't} \le (rl^m_{nn't} + rla^m_{nn't} + rlp^m_{nn't}) CAM^m_i \quad \forall i,\ n \in N,\ n' \in N,\ t,\ m \tag{13}$$

Constraint (13) ensures a feasible flow through a route, considering the reliability of the original, alternative, or special air routes. This constraint acts in combination with constraints (14) and (15).

$$rl^m_{nn't} + rla^m_{nn't} + rlp^m_{nn't} \le 1 \quad \forall n \in N, n' \in N,\ t, m \tag{14}$$

Constraint (14) selects at most one reliable route for supplying the HR items.

$$rl^m_{nn't} \le RO^m_{nn't};\ rla^m_{nn't} \le RA^m_{nn't};\ rpl^m_{nn't} \le RPL^m_{nn't} \quad \forall i,\ n \in N,\ n' \in N,\ t,\ m \tag{15}$$

Constraint (15) facilitates the selection of the original, alternative, or air route if they are reliable.

$$f^m_{inn't} \le k_n BN \quad \forall i,\ n \in N^t,\ n' \in N,\ t,\ m \tag{16}$$

Constraint (16) ensures the opening of a transit node before any flows go through it.

$$mr_{bnot} \le u_{bno}[del_{bn} \frac{P_n}{FS_n} PR_{bn}] \quad \forall b \in B,\ n \in N^d,\ o \in O,\ t \tag{17}$$

Based on the decision of the disaster monitoring cell (through the 0/1 parameter del_{bn}), constraint (17) estimates the requirements of the immediately-required resources at the demand nodes, and selects a feasible option for providing them.

$$\sum_{o \in O} u_{bno} = 1 \quad \forall b,\ n \in N^d,\ o \in O \tag{18}$$

Constraint (18) ensures that only one option is chosen for this purpose.

$$s_{en'nt} \ge w_{n'n}[des_{en} \frac{P_n}{FS_n} PER_{en}] \quad \forall e \in E,\ n' \in N^w,\ n \in N^d,\ t \tag{19}$$

Based on the confirmation of the applicability by the disaster monitoring cell (through the 0/1 parameter des_{en}), constraint (19) estimates the emergency rescue service requirements at demand nodes, and selects suitable DC nodes to provide the services.

$$s_{en'nt} \le hes_n CPS_{en} EQ_e \quad \forall e \in E,\ n' \in N^w n \in N^d,\ t \tag{20}$$

Constraint (20) limits the rescue services within the capacity of the DC nodes to provide such services.

$$w_{n'n} \le hes_n \quad \forall n \in N^w,\ n' \in N^d \tag{21}$$

Constraint (21) ensures that a DC node is open before it can provide rescue services to demand nodes.

$$EX_{gnn'} \le l_{n'n}[dx_n \frac{P_n}{FS_n} PXR_{gn}] \quad \forall g \in G,\ n \in N^d,\ n' \in N^w \tag{22}$$

Constraint (22) estimates the extended-time rehabilitation resource supports for the demand nodes based on the applicability of such services as decided by the disaster monitoring cell (though the 0/1 parameter dx_n), and assigns suitable DC nodes to provide the resources.

$$EX_{gnn'} \le dxr_n CPX_{gn} \quad \forall g \in G, n \in N^w n' \in N^d \tag{23}$$

Constraint (23) limits the shipments of extended time resources at a DC node within its capacity to provide such services to a demand node.

$$l_{nn'} \leq dxr_n \qquad \forall n \in N^w,\ n' \in N^d \qquad (24)$$

Constraint (24) ensures that a DC node is open before it is designated for providing extended time resource services to demand nodes.

$$a_{nn'}, w_{nn'}, l_{nn'} = \{0, 1\},\ \forall n, n' \in N; dxr_n, v_n, k_n, dx_n, hes_n, des_n = \{0, 1\},\ \forall n \in N; c_m = \{0, 1\}, m \in M$$
$$rl^m_{inn'}, rla^m_{inn'}, rlp^m_{inn'} = \{0, 1\}, \forall i \in I, m \in M, n, n' \in N; u_{bno} = \{0, 1\}, \forall b \in B, n \in N, o \in O \qquad (25)$$

Constraint (25) imposes integrality on the relevant variables.

We may note here that the proposed model ensures a level of service by supplying the required HR items to the demand nodes through constraints (2), (7), and (10). The model also includes air routes (see constraints (15) and (16)) if other routes for supplying HR items fail. The same approach is taken to ensure the delivery of the rescue services (see constraints (19)–(21)) and the extended time services (see constraints (22)–(24)). The optimization process focuses on cost minimization while at the same time it ensures the delivery of the required services to the demand points. Ensuring the supply of HR items within an optimum cost structure addresses the usual expectations of the disaster affected communities and of the agencies in charge that are operating under tight budgets.

Although the model includes the supply of HR items, emergency resources, rescue services, and extended-time services, humanitarian logistics include several other services and supports including the repair of roads and bridges, restoring the ecological conditions, restoring power supplies and other utility services, etc. As such it is evident that defining the service level in a disaster situation is often difficult, if not impossible. Moreover, maximizing the service level implies higher costs to the relief agencies, which in most cases they may not be able to bear. Considering the inclusion of select mitigation issues in the model, we have not taken the approach of optimizing the service level. However, it may be mentioned here that the mitigation issues for a disaster situations are complex.

4. A NUMERICAL EXAMPLE

A numerical example that closely resembles the situation faced by a flood-prone Asian country is illustrated here. In this scenario, 17 southern low-land districts of the country are badly affected by a recent flood. The demand zones/districts are supplied from 13 centers nearby (the DC nodes) that receive relief aid from 6 supply centers (the supply nodes) located at various parts of the country. The 6 supply nodes are connected to the DC nodes via a transportation network of highways, railways, waterways, and air routes. The network consists of 30 nodes that include the 6 supply nodes (nodes 1, 2, ⋯, 6), the 13 DC nodes (18, 19, ⋯, 30), and the remaining 11 nodes which work as transit nodes for connecting the highways, railways, waterways, and mixed mode transports routes. The demand nodes are supplied with HR items through designated DC nodes.

The distribution network diagram in Figure 1 presents the connecting communication arcs in terms of the applicable transportation modes (railway, highway, water ways, and air routes), and schematic positions of the supply nodes (1 to 6), the DC nodes (18 to 30), and the demand nodes (1 to 17). The suitability of the communication arcs for the various transportation modes are dynamically updated in each period using a 0–1 reliability parameter based on status reports communicated by the disaster monitoring cell operated by government agencies. If an existing arc connecting two nodes fails, alternative arcs through highway and waterway modes are available. When both the existing and alternative routes for transporting HR items become unavailable, the proposed model tries to generate different routes (i.e., arc combinations in mixed modes) or allocate air transportation modes.

Table 3 presents the estimated requirements of a typical relief operation for supplying HR items to 5 demand nodes, and the general estimation basis for resource support, rescue services, and extended-time rehabilitation support at the demand nodes.

This estimation is based on the extent of the disaster as reported by the disaster monitoring cell and the data available through census reports and national statistical data bases on family size, and the assumed average requirements per family. Input data on cost figures, per family requirements, population figures, transportation times and others are randomly generated considering data ranges in similar practical disaster situations.

The requirement estimates for emergency services and resource supports are in terms of the number of families of average size, and the HR item estimates are per family, in order to generalize the cost computations at different times, locations and prices. Table 3 includes the typical basic inputs to the model relevant to demand nodes. Other input data, such as the road reliability variables (obtained from the national monitoring cell dynamically, period to period), capacities of standard transport modes, and the procurement, transportation and distribution costs are not included to save space.

The model was solved for the example problem using LINGO 9 on a standard PC in approximately 5 minutes. The solution involved 21,651 variables in total, including 9,383 integer variables, and 19,757 constraints.

Table 4 presents the typical model output on the flow of HR item 1 (food packets for adults) in period 1 to DC nodes using reliable routes and suitable transportation modes in the network (Figure 1). It also shows the

Table 3. Input data

Table 3A. The estimated requirements of a typical relief operation for supplying HR items to 5 demand nodes

	Demand node				
	1	**2**	**3**	**4**	**5**
No. of families	226,200	295,700	796,200	1,848,800	655,800
Families that need HR items (%)	1	1	1	1	1
7-day requirements/family	Family size U(3, 7), Adults U(3, 4)/family, Children U(2, 3)/family				
Food for adults (packets)	22	27	21	28	21
Food for children (packets)	18	15	19	20	16
Water	42	21	25	49	35
Medicine	1	1	1	1	1

U: estimated per-family requirements of HR item at demand node based on a uniform distribution.

Table 3B. General estimation basis for computing rescue services, resource support and extended time services at a demand node

	Fixed cost ($)	Cost/family ($)	Capability of covering in one period (no. of families)
Rescue service[a)]			
Rescue team	2,000	U (250, 350)	200
Helicopter	35,000	U (300, 400)	400
Engine boat	10,000	U (200, 300)	400
Resource support[b)]			
Shelter			
Option 1	10,000	U (150, 250)	200
Option 2	1,500	U (250, 350)	20
Option 3	20,000	U (50, 100)	200
Hospital service			
Option 1	40,000	U (400, 600)	
Option 2	75,000	U (150, 205)	
Option 3	20,000	U (200, 400)	
Others (e.g., power source)			
Option 1	5,000	U (50, 150)	
Option 2	50,000	U (15, 30)	
Option 3	20,000	U (30, 50)	
Extended-time service[c)]			
Schools for children[d)]	20,000	40	
Home repair/rebuilding	5,000	50	
Cloth/medical support	5,000	500	

U: estimated per-family requirements of HR item at demand node based on a uniform distribution.
[a)] Required by U (0.0075%, 0.01%) of families; applicable in periods 1 and 2.
[b)] Required by U (0.1%, 0.15%) of families; applicable in all periods.
[c)] Required by U (0.005% to 0.008%) of families; applicable in general.
[d)] One school per 300 families.

distribution of the item from DC nodes to demand nodes. For example, using highway transport (trucks), 79,832 units of the item are directly shipped from supply node 1 to DC node 18 (via route 1–18; Figure 1), which are finally distributed to demand node 2 (via route 18–2; Figure 1). HR items are often transported to DC nodes

Table 4. Typical transportation and distribution for HR item 1 in period 1

Transport mode	Supply to		Quantity (packet) in		From DC node to demand nodes (packet)	Distributed quantity
	Transit	DC	Transit	DC		
Highway		1–18		79,832	18–2	79,832
Highway		2–19		216,970	19–1 (49,760), 19–3 (16,721)	216,970
Rail	**2–13**		**375,000**			
Highway	**3–13**		**19,311**			
Highway		3–21		202,726	21–4 (280,388), 21–6 (297,338)	577,726
Waterway		3–21		375,000		
Mixed	**4–13**		**141,587**			
Waterway		4–20		375,000	20–4 (237,289), 20–5 (137,711)	375,000
Rail	5–6		356,776			
Highway	5–14		239,160			
Rail	6–16		375,000			
Highway		**13–23**		**166,787**	23–7	166,787
Highway		6–25		204,352	25–8 (155,617), 25–9 (293,355), 25–10 (65,415), 25–11 (59,076)	573,463
Rail		**13–25**		**369,111**		
Highway		6–28		375,000	28–12 (25,538), 28–15 (114,302), 28–16 (107,584)	477,424
Mixed		6–28		102,424		
Rail		14–26		239,161	26–13(195,541), 26–14(43,620)	239,161
Highway		16–29		375,000	29–16 (105,903), 29–17(269,097)	375,000

HR: humanitarian relief, DC: distribution center.

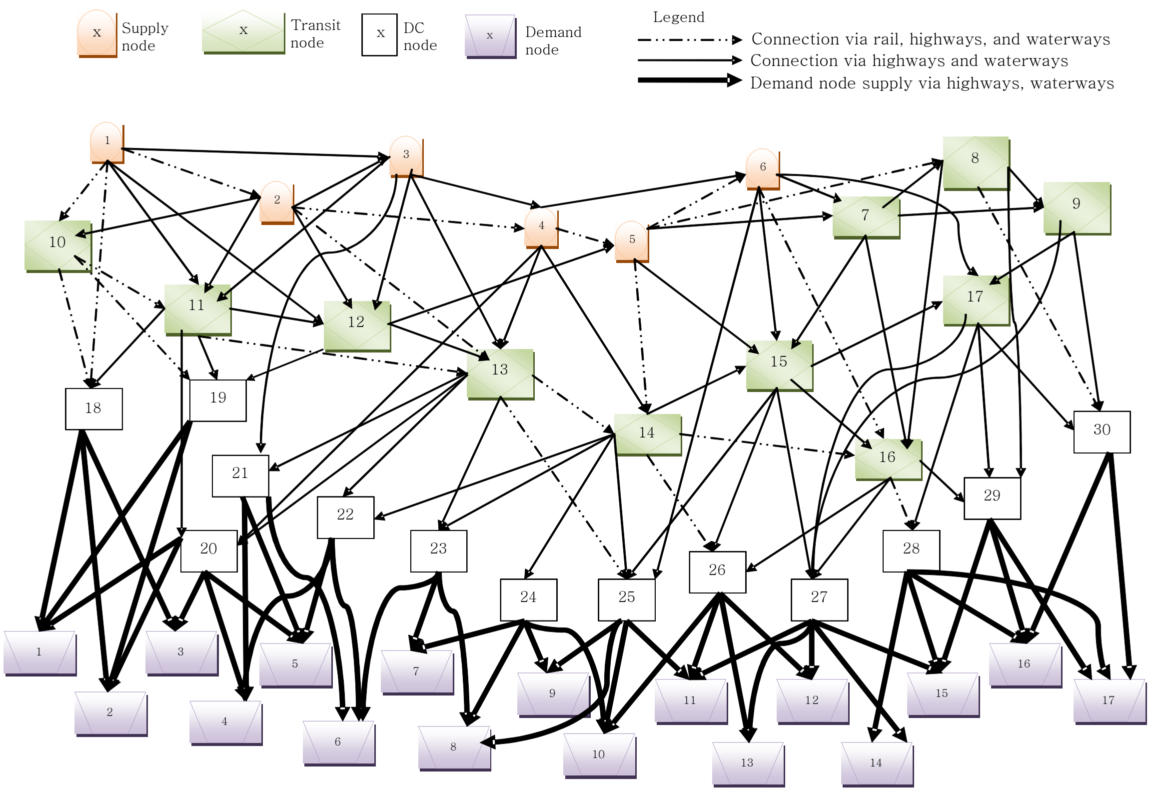

Figure 1. Distribution network. DC: distribution center.

through transit nodes when economically suitable and reliable direct routes to DC nodes are not available. To illustrate, using railway, highway and mixed transport modes, supply nodes 2, 3, and 4 shipped to transit node 13 (via routes 2–13, 3–13, 4–13), respectively, 375,000, 19,311, and 141,587 units for a total of 535,898 units at node 13. From node 13, 166,787 units are shipped to node 23 (via route 13–23) and 369,111 units to node 25 (via route 13–25). The DC nodes 23 and 25 finally distributed the items to various demand nodes as may be observed in Table 4.

Table 5 presents the model output on the assessment of HR item requirements and their optimum supply locations for procurement and storage. The results are presented for period 1 only. The assessment procedure will be the same for the other two periods. For example, the model decided to procure a total of 3,081,362 units of HR item 1 for period 1 of which 79,832 units are to be stored at supply node 1; 591,970, units to be stored at supply node 2, etc.

Table 6 presents the typical model output on assessment of the requirements of emergency resource supports (such as shelter, hospital services, and other resources, e.g., power sources). For example, 444 families at demand node 2 needed shelter immediately, and the cost-effective option selected by the model is to move the families to an already available shelter in a nearby state, or to a safe location nearby.

Table 7 presents the typical model outcome on the assessment of rescue services needed at the affected demand nodes. For example, demand node 1 needs emergency rescue services by a trained rescue team for 25

Table 5. Assessment of humanitarian relief (HR) item requirements and their storage locations in period 1

HR item	Supply node						Total
	1	2	3	4	5	6	
1	79,832	591,970	597,037	516,587	595,936	700,000	3,081,362
2	47,637	428,470	418,590	420,780	430,206	440,000	2,185,683
3	148,978	845,000	838,956	833,681	840,648	858,182	4,365,445
4	2,957	25,360	25,000	19,540	27,651	24,780	125,288

Table 6. Typical model output on assessment of emergency resource requirements by the affected demand nodes

Demand node	Resource type	Option selected by model	Needed by no. of families
2	Shelter	3 (moving to a safe city or location)	444
	Shelter	3 (moving to a safe city or location)	1,849
4	Other services	2 (repair existing power and utility facilities)	2,588
5	Hospital	2 (repair existing hospitals)	918
⋮	⋮	⋮	⋮
12	Shelter	3 (moving to a safe city or location)	1,179
	Hospital	2 (repair existing hospitals)	1,179
14	Hospital	2 (repair existing hospitals)	203
15	Other services	2 (repair existing power and utility facilities)	547
16	Shelter	3 (moving to a safe city or location)	1,027
	Hospital	2 (repair existing hospitals)	1,027

Table 7. Typical model output on assessment of emergency rescue service requirements by the affected demand nodes

Demand node	Rescue service	Provided by DC	No. of families needing rescue service
1	1 (trained rescue team help)	20	25
	3 (rescue by boat and other logistics)	20	23
2	3 (rescue by boat and other logistics)	20	87
⋮	⋮	⋮	⋮
10	1 (trained rescue team help)	25	27
12	1 (trained rescue team help)	28	101
	2 (helicopter rescue)	25	105
14	2 (helicopter rescue)	28	19
	3 (rescue by boat and other logistics)	28	52
15	1 (trained rescue team help)	28	50
	2 (helicopter rescue)	28	56
	3 (rescue by boat and other logistics)	28	52
17	1 (trained rescue team help)	28	100

DC: distribution center.

families, which are provided from DC node 20. As may be observed in Table 7, the disaster monitoring cell deployed the rescue service resources at three DC nodes, 20, 25, and 28, in order to provide the 3 types of services to demand nodes.

Table 8 describes the typical model output on assessment of the extended-time support requirements by the affected demand nodes. The long-term support responsibilities are assigned to five DC nodes (20, 21, 23, 27, and 28) to monitor the support activities. To illustrate, demand node 3 needed extended-time support in terms of schools for children for 69 families, which has been supported from DC node 20. Based on the previous discussion, this type of extended-time support is provided by international and government organizations to ensure resource availability and the required monitoring.

Based on the discussion of the model output, it is apparent that the model is capable of assessing several crucial disaster relief requirements based on information about the extent of the disaster, as reported by the disaster monitoring cell, and the data available through census reports and national statistical data bases on family size, and the assumed average requirements per family.

5. CONCLUSIONS

The research introduced an integer linear programming model-based systematic procedure for assessment of emergency relief requirements in disaster affected areas using readily available government data, national media reports or similar data from satellite scanning on the extent of the damage just after a disaster occurs. Such assessment is crucial for extending emergency rescue services, sending HR items, such as food, water, and emergency medicines to the affected population of the disaster-hit areas. In addition, the assessment will create the basis for procuring relief items from international and national donor agencies as well as government organizations.

In addition to the assessment, the proposed model includes an effective mitigation plan covering optimum routing and distribution of HR items considering network link reliability, capacity of transportation modes and the optimum location of the supply, transit, and DC nodes. The model also facilitates the designation of select DC nodes for providing emergency resource supports, rescue services and extended-time support services to the affected demand zones. To identify such affected zones, the model relies on input from national disaster monitoring cells based on their on-site investigations. The model generates a plan for the deployment of the required resources to the assigned DC nodes based on its assessment of the HR item requirements at the demand nodes.

The model includes a provision for updating the

Table 8. Typical model output on assessment of long-term support requirements for affected demand nodes

Demand node	Long-term support	Provided from DC	No. of families needing support
3	1 (school for children)	20	69
	2 (home repair or rebuilding help)	20	80
	3 (clothes and medical support)	20	71
4	1 (school for children)	20 and 21	64 + 85 = 149
	2 (home repair or rebuilding help)	20	178
	3 (clothes and medical support)	20	176
5	1 (school for children)	20	56
	2 (home repair or rebuilding help)	20	59
	3 (clothes and medical support)	20	64
6	1 (school for children)	21 and 23	115 + 9 = 124
	2 (home repair or rebuilding help)	21	112
	3 (clothes and medical support)	21	121
⋮	⋮	⋮	⋮
13	1 (school for children)	27	76
	2 (home repair or rebuilding help)	27	75
	3 (clothes and medical support)	27	80
15	1 (school for children)	27 and 28	5 + 38 = 43
	2 (home repair or rebuilding help)	27	41
	3 (clothes and medical support)	28	45
17	1 (school for children)	28	80
	2 (home repair or rebuilding help)	28	80
	3 (clothes and medical support)	28	88

DC: distribution center.

disaster damage assessment and mitigation plan dynamically as time passes. The model may be used in preparing assessment and mitigation plans for several disaster-affected zones together, employing multiple supply, transit, and DC nodes and route networks.

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