Journal of Marine Science and Technology

Volume 30 | Issue 2 Article 1

Optimal Deployment of Flood Emergency Response Materials under Stochastic Demands

Shangyao Yan
Department of Civil Engineering, National Central University, Taoyuan 32001, Taiwan

Jenn-Rong Lin
Department of Civil Engineering, National Central University, Taoyuan 32001, Taiwan, jrlin@email.ntou.edu.tw

Chia-Fu Ku
Department of Civil Engineering, National Central University, Taoyuan 32001, Taiwan

Recommended Citation
Yan, Shangyao; Lin, Jenn-Rong; and Ku, Chia-Fu (2022) "Optimal Deployment of Flood Emergency Response Materials under Stochastic Demands," *Journal of Marine Science and Technology*: Vol. 30: Iss. 2, Article 1.
DOI: 10.51400/2709-6998.2568
Available at: https://jmstt.ntou.edu.tw/journal/vol30/iss2/1

RESEARCH ARTICLE

Optimal Deployment of Flood Emergency Response Materials under Stochastic Demands

Shangyao Yan [a], Jenn-Rong Lin [b,*], Chia-Fu Ku [a]

[a] Department of Civil Engineering, National Central University, Taoyuan 32001, Taiwan
[b] Department of Transportation Science, National Taiwan Ocean University, Keelung 20224, Taiwan

Abstract

This study aims to develop a planning model for the deployment of flood emergency response materials under stochastic demands. For ease of modeling, a deterministic demand model is first proposed, from which the stochastic model is further extended. These models are used to determine the allocation of materials the transport truck routes and distribution of the stockpiled materials to emergency sites. The models are formulated as multiple integer network flow problems with special side constraints which are characterized as NP-hard in terms of optimization. To solve the complicated stochastic model efficiently, we also develop a solution algorithm based on a problem decomposition technique coupled with a variable fixing technique. Finally, to preliminarily evaluate the proposed models and solution algorithm, we perform numerical tests using data related to a Taiwan flood emergency response system. The test results are good, indicating the potential usefulness of the models and solution algorithm in practice.

Keywords: Flood emergency response, Material deployment, Time-space network, Stochastic demand, Solution algorithm

1. Introduction

Due to global warming and extreme climate change, in recent years the frequency and severity of typhoons or hurricanes has increased dramatically. At the same time, the damage caused by storms and floods has become more costly, as more and more people choose to reside closer to rivers, on flood plains and other vulnerable areas. The more serious consequences include loss of life and property in the catchment or downstream areas. Hence, governments need to implement prompt and efficient flood emergency response systems to fight the threat of flooding as a result of catastrophic events.

Being located in the western part of the North Pacific Ocean, Taiwan is directly affected by several typhoons each year. During the period from 1991 to 2014, there were 171 flooding events caused by typhoons or extreme rainfall [1]. Typhoons and extreme rainfall events may trigger flooding simply because of the sheer volume of the precipitation. To avoid catastrophic flooding, the Taiwan government has developed a flood-fighting protocol, as explained in its River Management Regulations. This protocol defines the flooding season as extending from May to November when the majority of typhoons strike Taiwan. Before the flooding season begins, the River Management Office and the local authorities are directed to team up to form flood-fighting command teams. These command teams are then required to determine suitable locations for the storage of sufficient flood emergency response materials in advance, in order to promptly and efficiently respond to an emergency flooding event, such as a levee breach.

In practice, when a levee is breached during a flood event, the responsible command team will first

Received 3 January 2022; revised 8 February 2022; accepted 9 March 2022.
Available online 17 May 2022.

* Corresponding author.
E-mail address: jrlin@email.ntou.edu.tw (J.-R. Lin).

https://doi.org/10.514/2709-6998.2568

send out geotechnical and hydraulic engineers to investigate the extent of the damage and determine the amount of flood emergency response materials required to close the breaches as rapidly as possible to prevent further damage. The required materials are transported by a contractor. Since the focus of the command team is to close the breaches as soon as possible, the contractor is required to have a sufficiently large fleet of vehicles to transport the required amount of materials within a short period of time (generally within 24 h). In addition, the contractor is paid according to how many units of response materials are transported within the required time period. The decisions on how to transport the materials are made solely by the contractor, as long as they are transported to the designated sites within the required time period. In real operations, the main consideration of the command team during the tactical planning stage is that the materials be delivered within the required time period following the flood event. Given this requirement, the authorities generally look for a minimum cost for payment to the contractor.

Currently, command team decisions about the deployment of flood emergency response materials, coupled with the response to emergency events, are made manually based on personal experience and historical data, which may not be efficient enough to prevent more extensive damage. It would therefore be useful to develop a flood emergency response material deployment model that takes into consideration the contract for efficient truck routing and the dispatching of response materials.

In addition, historical factors and circumstances related to emergency events may change. For example [2], pointed out that although levee breaches are likely to be in the same general vulnerable locations or locations close to previous flooding events, the magnitude of the breaches may vary. Since the magnitude of a breach is not known in advance, the amount of material required to carry out emergency repairs may also vary. Therefore, there is a need to develop a model that takes into consideration the stochastic nature of levee damage due to flooding.

The increase in the frequency and severity of natural disasters caused by earthquakes and major storms in recent years has given rise to more and more studies related to emergency logistics, specifically, emergency relief logistics and emergency response logistics. Emergency relief logistics are aimed at providing the necessary supplies to those affected and rescuing them during an emergency while, emergency response logistics, in contrast, are aimed at repairing damaged infrastructure and preventing further catastrophic damage. Both types of efforts can soften the impacts of emergency events and reduce the losses incurred to residents living within the affected regions. However, to date, most studies have focused on emergency relief logistics, including, for example, strategic planning for flood rescue resource distribution systems [3], coordination of relief logistics and evacuation operations [4,5], vehicle routing in relief logistics and evacuation operations [6,7], the pre-positioning of emergency relief supplies [8,9] and optimization of relief supplies for flooding emergencies [10]. For details of the emergency relief logistics problem, please refer to [11,12]. Özdamar [13], proposed a planning system combining mathematical model with a route management procedure for coordinating helicopter operations for disaster relief. The system planned helicopter operations for delivering medical supplies and evacuating injured people from disaster areas. Bozorgi-Amiri et al. [14], discussed humanitarian relief logistics and built a multi-objective model aimed at the minimization of the total expected value and the variance of the total cost of the relief chain, under uncertain demands, supplies and the cost of procurement and conveyance.

Past studies related to flood emergency response logistics focusing on transportation network repair, relief supplies, repair crew scheduling, flood emergency monitoring and estimation of relief supply demand include those by [10,15–22]. There have been few studies addressing the deployment of flood emergency response material, especially with consideration of the uncertain magnitude of response requests. Thus, we develop two mathematical models, a deterministic one and a stochastic one, for the deployment of materials for a flood emergency response system.

The key tactical planning decisions considered are: the level of inventory of response materials stored at each stockpile location, the transport truck routing and how the available flood emergency response materials should be transported from stockpile locations to each emergency site. The number of stockpile locations is assumed to be known in advance, since they have been predetermined by the command team, and the locations of flood emergency sites are also assumed to be known, although the magnitude of the flood emergency events is uncertain. The focus of these models is on short-term tactical deployment decisions regarding the levels of inventory of stockpiled flood emergency response materials and decisions regarding transport truck routing and the distribution of flood emergency response materials to emergency sites.

The rest of this paper is organized as follows. Section 2 describes the two models. Section 3 develops the solution algorithm. Section 4 presents the results of numerical tests. Finally, some conclusions and suggestions are drawn in Section 5.

2. Modeling approach

The network structure and the mathematical formulation for determining the best levels of inventory of stockpiled flood emergency response materials and the associated transport truck routing and distribution of these materials to flood emergency sites under stochastic demands are discussed in this section. The network technique provides an efficient way to address multiple vehicle/entity/commodity routings (e.g., see [23−26]. Thus, we design a time-space network to denote the allocation of flood emergency response materials among stockpile locations as well as the dispatch of trucks to transport the materials to sites impacted by the flooding events. For ease of modeling, we first develop a deterministic flood emergency response materials deployment model (DFMDM) with the objective of minimizing the total system cost. To deal with the issue of stochastic demand in practice, we further extend the deterministic model to develop a stochastic flood emergency response materials deployment model (SFMDM). To ensure the compliance of the model to real practices, the following assumptions are made:

1. The response to the flood emergency event must be completed within 24 h in order to prevent further damage, meaning that all demands for emergency materials for the specific flood emergency event have to be satisfied within the required response time.
2. The stockpile locations are assumed to be known and fixed because they have been pre-determined by the command team.
3. The locations of emergency sites are known, but the magnitudes of the emergency events are uncertain. The required amount of emergency response materials associated with an emergency event is associated with its magnitude. For the deterministic model, the amount of material required at a site is calculated as an average of all stochastic demands.
4. Only one type of truck is used to transport response materials. In addition, a truck can only be dispatched to only one emergency site per trip; multiple stops are not allowed by contract.
5. The contractor in charge of distributing the response materials is paid by the authorities according to how many units of material they transport. In particular, the operating cost for distributing a unit of response materials to an emergency site is related to the type of material and the distance from the stockpile location to the emergency site and is calculated by taking the sum of cost for loading, unloading and transportation cost. Note that the operating costs of the trucks are not considered in the contract.
6. The models are designed to assist the decision-making authorities. The objective of the models is to minimize the total cost/expected cost, given the requirement that the materials be transported to the designated emergency sites within a specified time period.

2.1. Network structure

There are two types of networks designed for formulating the movement of transport trucks and emergency response materials.

2.1.1. The truck-flow time-space network

The time-space network indicating the potential movements of transport trucks in the dimension of time and space is shown in Fig. 1. The vertical axis represents the duration of the analysis period, while the horizontal axis shows the stockpile locations and emergency sites (the locations where flood emergency events have occurred). The duration of the analysis period is equal to the longest time within which the transportation of all materials must be completed. Based on real practices, the duration of the analysis period is set to be one day. Each node, except for the dummy supply node, denotes the location of a stockpile or flood emergency site at a specific time within the analysis period. In practice, the decision maker may have to make a trade-off between solution accuracy and efficiency when determining a suitable node interval. The movement of each transport truck is represented by an arc. The arc flows express the flow of transport trucks in the network. The five types of arcs are defined below.

(1) Service arc

A response to a flood emergency service request is represented by a service arc (see (1) in Fig. 1). The response requires the dispatch of a truck which will travel from a stockpile location to an emergency site. The dispatch contains information about the dispatch location, the arrival location, the dispatch time, the required travel time and the arrival time.

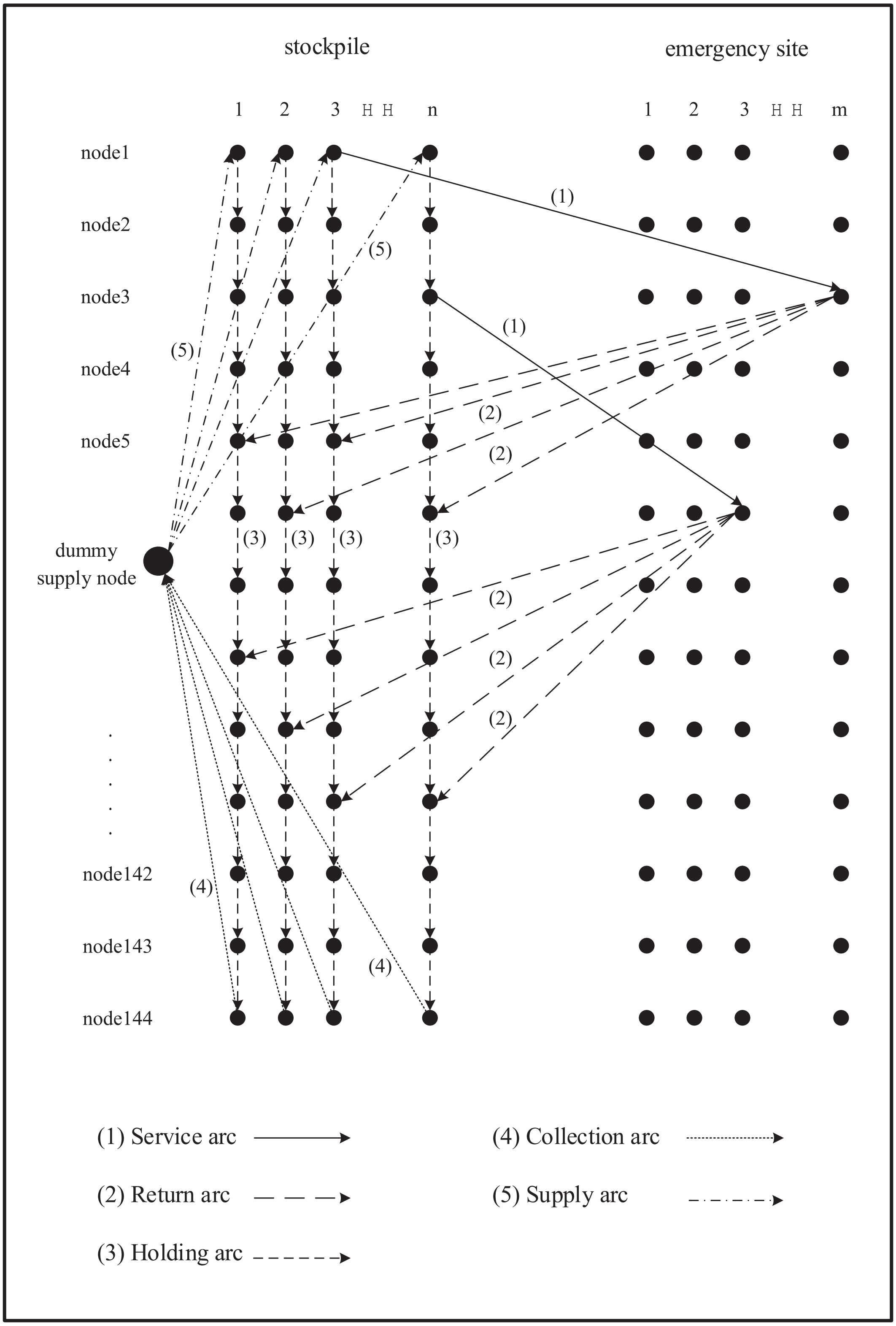

Fig. 1. The truck-flow time-space network.

The required travel time from a stockpile location to an emergency site is set to be equal to the actual travel time plus the loading time required at the stockpile location and the unloading and service time required at the emergency site. The arrival time at the emergency site is thus equal to the dispatch time at the stockpile location plus the travel time between the two locations. All possible transport truck dispatches between a stockpile location and an emergency site are considered in the network as long as the arrival times are within the response time limit. The arc cost is equal to zero (refer to assumption 5). Note that the handling costs for transporting response materials to serve a flood emergency response request are considered in the response material flow arcs which will be discussed later. If there is a need to consider the contractor's operating costs for dispatching a truck in response to a flood emergency service request in other applications, it can be easily set as the arc cost. The decision as to whether or not to dispatch a response truck from the stockpile location to the emergency site is represented by the arc flow. Therefore, the arc flow is a binary variable. If a response truck is dispatched from the stockpile location to the emergency site using this arc, the value of the arc flow is one, which is the upper bound. Otherwise, the value of the arc flow is zero, which is the lower bound.

(2) Return arc

The return of a dispatched truck from an emergency site to a stockpile location after serving an emergency response request is represented by a return arc (see (2) in Fig. 1). The arc cost of a return arc is zero (refer to assumption 5). The decision as to whether or not a response truck returning from an emergency site should return to the stockpile location is represented by the arc flow. Therefore, the arc flow is a binary variable. If a response truck returns to the stockpile location using this arc, the value of the arc flow is one. Otherwise, the value of the arc flow is zero.

(3) Holding arc

A holding arc (see (3) in Fig. 1) is created to represent the holding of trucks (which are not dispatched) but stay at a stockpile location for a period of time. The arc cost denotes the cost incurred for holding trucks at a stockpile location and is equal to zero (refer to assumption 5). Obviously, the largest number of trucks that can stay at a stockpile location is equivalent of the size of the fleet deployed in the flood emergency response system. Therefore, the arc flow's upper bound is set to be the fleet size. If no truck is held at the stockpile location, the value of the arc flow is zero, which is the lower bound. Note that there is no holding arc at an emergency site because the response should be prompt.

(4) Collection arc

The return of trucks from a stockpile location to the dummy supply node is represented by a collection arc (see (4) in Fig. 1). The arc cost is zero (refer to assumption 5). Obviously, the largest number of trucks is equivalent to the fleet size. Therefore, the arc flow's upper bound is set to be the fleet size. If there is no truck to be collected from the stockpile location, the value of the arc flow is zero, which is the arc flow's lower bound.

(5) Supply arc

The deployment of trucks from the dummy supply node to a stockpile location is represented by a supply arc (see (5) in Fig. 1). The arc cost denotes the fixed cost for allocating a truck at a stockpile location to service the flood emergency response requests. In this study, the arc cost is set to be zero (refer to assumption 5). Obviously, the largest number of trucks that can be dispatched to a stockpile location is equivalent to the fleet size. Therefore, the arc flow's upper bound is set to be the fleet size. If no truck is dispatched to the stockpile location, the value of the arc flow is zero, which is the arc flow's lower bound.

2.1.2. *The material-flow time-space network*

As shown in Fig. 2, the time-space network of material flows denotes the potential movement of flood emergency response materials between two locations within a certain time span. Each layer in the material-flow time-space network represents the movement of a specific type of flood emergency response material movement. The movement of materials in the material-flow time-space network must correspond to the movement of trucks in the truck-flow time-space network. The horizontal axis represents the flood emergency response material stockpile locations and the flood emergency sites, while the vertical axis represents the duration of the analysis period. As in the truck-flow time-space network, each node, except for the dummy supply node and the dummy demand node, denotes a stockpile location or a flood emergency site at a specific time. Each arc represents the movement of materials. The arc flows express the flow of materials in the network. Four types of arcs are defined as follows:

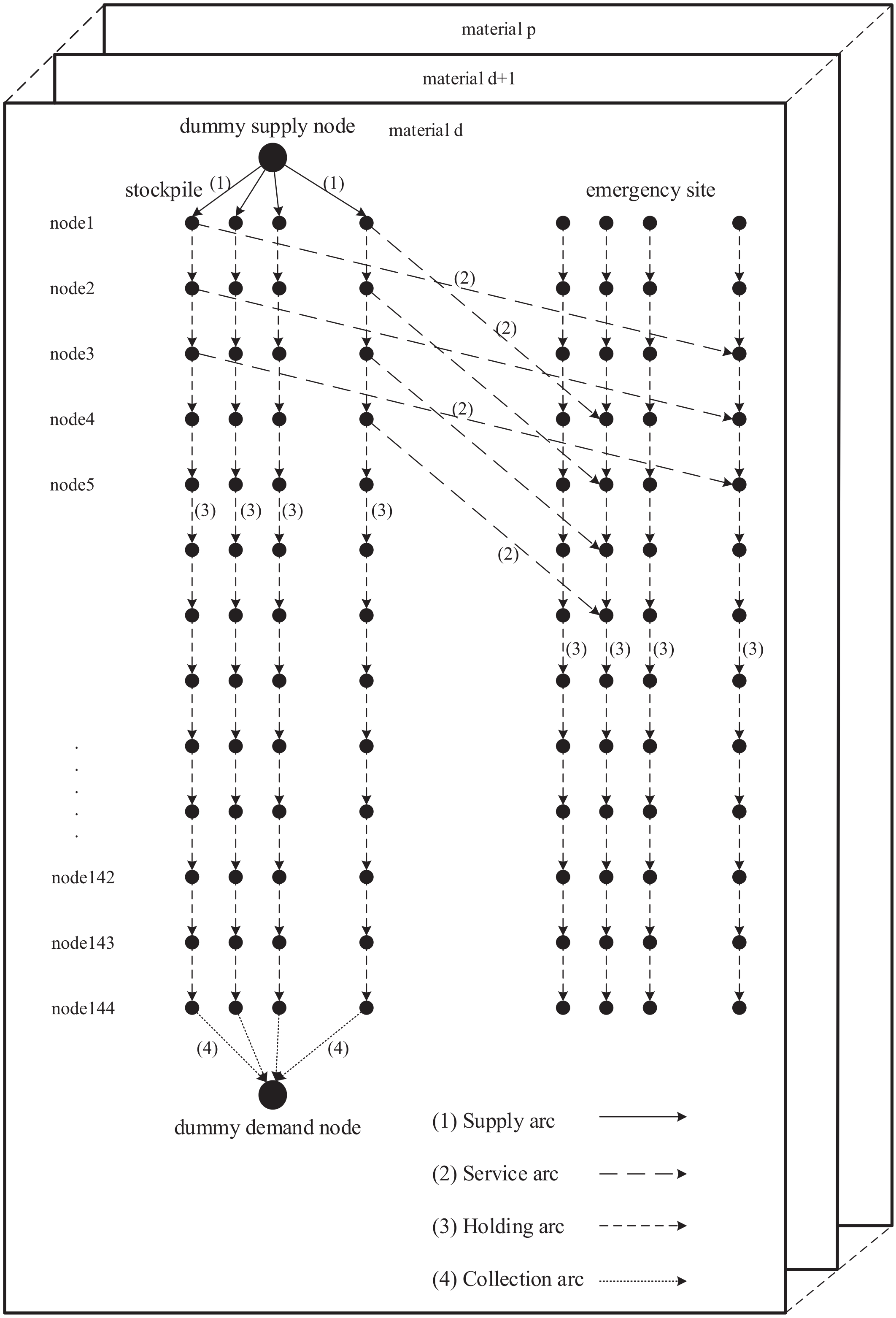

Fig. 2. The material-flow time-space network.

(1) Supply arc

The deployment of flood emergency response materials from the dummy supply node to a stockpile location at the beginning of the analysis period is represented by a supply arc (see (1) in Fig. 2), which corresponds to a supply arc in the truck-flow time-space network. The arc cost denotes the fixed cost for deploying one unit of response materials at a stockpile location. However, in this study, the arc cost is set to zero because the material manufacturing cost is roughly the same across all providers. It is thus a constant and can therefore be removed from the optimization. The arc flow's upper bound, which is the largest amount of materials that can be allocated to a stockpile location, should not exceed the storage capacity at that location. If there is none of this type of flood emergency response material allocated to that stockpile location, the value of the arc flow is zero, which is the arc flow's lower bound.

(2) Service arc

The movement of materials from a stockpile location to an emergency site within the associated block of time is represented by a service arc (see (2) in Fig. 2). All information regarding the material movement is identical to the corresponding truck dispatch information. The arc cost is equal to the payment from the authorities to the contractor for moving one unit of response material from the stockpile location to the emergency site. Note that the contractor in charge of distributing the response materials is paid according to how many units of material they transport. The arc flow denotes the number of units of emergency response materials that are transported from the stockpile location to the emergency site. The upper bound of the arc flow, which is the largest amount of materials that can be transported on a truck, should not exceed the capacity of the transport truck. If no material is transported to the emergency site on this trip, the value of the arc flow is zero, which is the lower bound of the arc flow.

(3) Holding arc

The storage of flood emergency response materials at a stockpile location for a specific period is represented by a holding arc (see (3) in Fig. 2). The arc cost is the unit storage cost for this period which is set to be a very small value, since the required storage space is provided by the river management office or local government. The maximum amount of materials that can be stored at a stockpile location cannot exceed the storage capacity, which is the upper bound of the arc flow. If no material is stored at this location during this period, the arc flow is zero, which is the lower bound.

(4) Collection arc

Unused flood emergency response material collected from a stockpile location and moved to the dummy demand node at the end of the analysis period is represented by a collection arc (see (4) in Fig. 2). The arc cost is set to be zero in this study. The arc flow's upper bound, which is the largest amount of materials that can be allocated to a stockpile location, should not exceed the storage capacity of at that location. If none of this type of material is allocated to the stockpile location, the value of the arc flow is zero, which is the lower bound.

2.2. Deterministic model (DFMDM)

The notations and symbols used for formulating the deterministic model are listed below.

Sets:

VN: the set of all nodes in the truck-flow time-space network;
VA: the set of all arcs in the truck-flow time-space network;
VNS: the set of all stockpile location nodes in the truck-flow time-space network;
VND: the set of all flood emergency site nodes in the truck-flow time-space network;
VAF: the set of all service arcs in the truck-flow time-space network;
GP: the set of flood emergency response materials;
MN^d: the set of all nodes in the material-flow time-space network for material d;
MA^d: the set of all arcs in the material-flow time-space network for material d;

Parameters:

CV_{ij}: arc (i,j) cost for the truck-flow time-space network;
CM_{ij}^d: arc (i,j) cost for the d^{th} material-flow time-space network;
UV_{ij}: arc (i,j) flow's upper bound for the truck-flow time-space network;
UM_{ij}^d: arc (i,j) flow's upper bound for the d^{th} material-flow time-space network;
V_d: the volume per unit of material d;
V: the volume capacity of a truck;
W_d: the weight per unit of the material d;
W: the weight capacity of a truck;
b_i^d: the supply of material d at node i in the d^{th} material-flow time-space network;
if node i represents the dummy supply node, $b_i^d = Q_d$ (i.e., total supply of the d^{th} material);
if node i represents a flood emergency site, $b_i^d = -D_{md}$ (i.e., demand of the d^{th} material for the m^{th} emergency site);
if node i represents the dummy demand node, $b_i^d = \sum_{j=1}^{m} D_{jd} - Q_d$ (i.e., the remaining inventory level of the d^{th} material);
otherwise, it is equal to zero;
INT: set of integers.

Decision variables:
x_{ij}: arc (i,j) flow in the truck-flow time-space network;
y_{ij}^{d}: arc (i,j) flow in the d^{th} material-flow time-space network.

The deterministic flood emergency response material allocation model (DFMDM) is formulated as an integer network flow problem with special side constraints as follows:

Min

$$\sum_{ij\in VA} CV_{ij} \times x_{ij} + \sum_{d=1}^{p} \sum_{ij\in MA^d} CM_{ij}^{d} \times y_{ij}^{d} \quad (1)$$

S.T.

$$\sum_{j\in VN} x_{ij} - \sum_{k\in VN} x_{ki} = 0, \qquad \forall i \in VN, \quad (2)$$

$$\sum_{j\in MN^d} y_{ij}^{d} - \sum_{k\in MN^d} y_{ki}^{d} = b_i^d, \quad \forall i \in MN^d, d \in GP, \quad (3)$$

$$\sum_{j\in VND} x_{ij} \le 1, \qquad \forall i \in VNS, \quad (4)$$

$$\sum_{d=1}^{p} V_d \times y_{ij}^{d} \le V \times x_{ij}, \qquad \forall ij \in VAF, \quad (5)$$

$$\sum_{d=1}^{p} W_d \times y_{ij}^{d} \le W \times x_{ij}, \qquad \forall ij \in VAF, \quad (6)$$

$$0 \le x_{ij} \le UV_{ij}, \qquad \forall ij \in VA, \quad (7)$$

$$0 \le y_{ij}^{d} \le UM_{ij}^{d}, \qquad \forall ij \in MA^d, d \in GP, \quad (8)$$

$$x_{ij} \in INT, \qquad \forall ij \in VA, \quad (9)$$

$$y_{ij}^{d} \in INT, \qquad \forall ij \in MA^d, d \in GP. \quad (10)$$

The objective function (1) minimizes the total cost, given that the responses to the flood emergency events must be completed within 24 h. The total cost includes the operating costs for truck usage and the handling costs for transporting the materials. Note that although the operating costs are zero in this study (refer to assumption 5), we retain the first item, i.e., the operating costs for truck usage, to retain a more general format that will be useful for other applications. Constraint (2) ensures that the truck-flow conservation hold for each node. Constraint (3) ensures that the material-flow conservation hold for each node and guarantees that the response requests at each emergency site node are satisfied. Constraint (4) ensures that each emergency site can only be serviced by at most one truck per time spot. Constraint (5) is the truck volume capacity constraint. Constraint (6) is the truck weight capacity constraint. Constraints (7) and (8) set the lower bounds and upper bounds for all arc flows. Constraints (9) and (10) ensure that all arc flows are integers.

It should be mentioned that the DFMDM can be suitably modified and applied by the contractor to solve the optimal truck routing and response material dispatching problem from stockpile locations to emergency sites in real-world operations, given the amount of required response materials and the associated emergency sites. The modifications are as follows: 1) the amount of response materials at all stockpile locations is fixed; 2) the operating costs for truck usage for the contractor can be set for all arcs in the truck-flow time-space network; and 3) the service arc cost in the material-flow time-space network is set to be the negative value of the revenue earned by the contractor for distributing one unit of response material from the stockpile location to the emergency site. Detailed modifications and tests of the model can be researched in the future.

2.3. Stochastic model (SFMDM)

In reality, the location and magnitude of flooding events triggered by typhoons or extreme rainfall that strike Taiwan will vary, although certain flood locations are known to be vulnerable to flooding. This means that the locations of emergency sites and the required amount of response materials are not deterministic but stochastic, varying year by year.

It is important that a suitable amount of flood emergency response materials be deployed to each stockpile location at the beginning of the analysis period. The amounts need to be sufficient to respond to differences in demand at various emergency sites, so that under all circumstances the required materials can be successfully delivered, via an effective truck routing plan by the contractor, within the required time period following each flooding event. Furthermore, the model should also minimize the total expected cost at the end of the analysis horizon.

To cope with this type of stochastic optimization problem, the DFMDM is modified to become a stochastic model, capable of considering all possible demand scenarios, each associated with a number of emergency sites and demands for response materials. Flood emergency response materials are deployed at stockpile locations at the beginning of the analysis period, but the delivery of response materials to the emergency sites, coupled with the planning of truck routes, may vary between demand scenario. Thus, the stochastic model is formulated as a two stage stochastic model [27,28], with the problem of the deployment of flood emergency response materials to stockpile locations being solved first (first stage decision), and the delivery of response materials from stockpile locations to the emergency sites, coupled with the truck routing plan for each demand scenario, being solved subsequently (second stage decision).

An integrated stochastic model is developed by efficiently modifying the DFMDM, as in [29]. In the first stage, decision variables corresponding to all demand scenarios are split and nonanticipativity constraints are then added to the stochastic model, ensuring that the first stage decisions are the same for all demand scenarios. This technique has been successfully adopted to develop effective stochastic programming models in the literature; for example, see [30]. The modifications of the DFMDM to create a stochastic model are described in detail below.

As in the deterministic model, the time-space network can be employed to represent the stockpile locations, flood emergency sites, flood emergency response materials inventory levels at stockpile locations, trucks dispatched and the movement of flood emergency response material under uncertain demands. The design of the time-space networks for the stochastic model is similar to that of the deterministic model. The building of the time-space networks in the stochastic model is not discussed again in detail. The definitions for the nodes and the types of arcs and the corresponding upper/lower bounds of the arcs are identical to those used in the deterministic model. However, in contrast to the deterministic model, which has only a single layer, the stochastic network has multiple layers, each corresponding to a demand scenario with a probability of occurrence. All possible demand scenarios need to be considered when making decisions about the deployment of emergency materials to stockpile locations. The supply arc flows associated with a stockpile location are the same for all layers, indicating that the deployment of flood emergency response materials to that stockpile location is set at the beginning of the analysis period (first stage decision). The other arc flows associated with an activity are not necessarily the same for all layers because the decisions in each layer are made by only considering the corresponding demand scenario (like the second stage decision).

Additional notations and symbols used to formulate the stochastic model are listed below.

Sets:

VN^s:	the set of all nodes in the truck-flow time-space network for demand scenario s;
VA^s:	the set of all arcs in the truck-flow time-space network for demand scenario s;
VNS^s:	the set of all stockpile nodes in the truck-flow time-space network for demand scenario s;
VND^s:	the set of all flood emergency site nodes in the truck-flow time-space network for demand scenario s;
VAF^s:	the set of all service arcs in the truck-flow time-space network for demand scenario s;
$MN^{d,s}$:	the set of all nodes in the d^{th} material-flow time-space network for demand scenario s;
$MA^{d,s}$:	the set of all arcs in the d^{th} material-flow time-space network for demand scenario s;
$MAE^{d,s}$:	the set of all supply arcs in the d^{th} material-flow time-space network for demand scenario s.

Parameters:

UV^s_{ij}:	arc (i,j) flow's upper bound for the truck-flow time-space network for demand scenario s;
$UM^{d,s}_{ij}$:	arc (i,j) flow's upper bound for the d^{th} material-flow time-space network for demand scenario s;
P_s:	the probability for demand scenario s;
τ:	the number of scenarios;
$b^{d,s}_i$:	the supply of material d at node i in the d^{th} material-flow time-space network for demand scenario s; if node i represents the dummy supply node, $b^{d,s}_i = Q_d$ (i.e., total supply of the d^{th} material for demand scenario s); if node i represents a flood emergency site, $\mathrm{b}^{\mathrm{d,s}}_{\mathrm{i}} = -\mathrm{D}^{\mathrm{s}}_{\mathrm{md}}$ (i.e., demand of the dth material for the mth emergency site demand scenario s); if node i represents the dummy demand node, $\mathrm{b}^{\mathrm{d,s}}_{\mathrm{i}} = \sum_{\mathrm{j=1}}^{\mathrm{m}} \mathrm{D}^{\mathrm{s}}_{\mathrm{jd}} - \mathrm{Q}_{\mathrm{d}}$ (i.e., the remaining inventory level of the dth material demand scenario s); otherwise, it is equal to zero.

Decision variables:

x^s_{ij}:	arc (i,j) flow in the truck-flow time-space network for demand scenario s;
$y^{d,s}_{ij}$:	arc (i,j) flow in the d^{th} material-flow time-space network for demand scenario s.

The stochastic flood emergency response material allocation model (SFMDM) is formulated as follows:

Min

$$\sum_{s=1}^{\tau} p^s \left[\sum_{ij\in VA^s} CV_{ij} \times x^s_{ij} + \sum_{d=1}^{p} \sum_{ij\in MD^{d,s}} CM^d_{ij} \times y^{d,s}_{ij} \right] \tag{11}$$

S.T

$$\sum_{j\in VN^s} x_{ij}^s - \sum_{k\in VN^s} x_{ki}^s = 0, \quad \forall i\in VN^s,\ s=1\ldots\tau, \tag{12}$$

$$\sum_{j\in MN^{d,s}} y_{ij}^{d,s} - \sum_{k\in MN^{d,s}} y_{ki}^{d,s} = b_i^{d,s},\ \forall i\in MN^{d,s},\ d\in GP,\ s=1\ldots\tau, \tag{13}$$

$$\sum_{j\in VND^s} x_{ij}^s \le 1, \quad \forall i\in VNS^s,\ s=1\ldots\tau, \tag{14}$$

$$\sum_{d=1}^{p} V_d \times y_{ij}^{d,s} \le V \times x_{ij}^s, \quad \forall ij\in VAF^s, s=1\ldots\tau, \tag{15}$$

$$\sum_{d=1}^{p} W_d \times y_{ij}^{d,s} \le W \times x_{ij}^s, \quad \forall ij\in VAF^s, s=1\ldots\tau, \tag{16}$$

$$y_{ij}^{d,1} = y_{ij}^{d,2} = y_{ij}^{d,3} = \ldots = y_{ij}^{d,\tau}, \quad \forall ij\in \bigcup_s MAE^{d,s}, d\in GP, \tag{17}$$

$$0 \le x_{ij}^s \le UV_{ij}^s, \quad \forall ij\in VA^s,\ s=1\ldots\tau, \tag{18}$$

$$0 \le y_{ij}^{d,s} \le UM_{ij}^{d,s}, \quad \forall ij\in MA^{d,s}, d\in GP, s=1\ldots\tau, \tag{19}$$

$$x_{ij}^s \in INT, \quad \forall ij\in VA^s,\ s=1\ldots\tau, \tag{20}$$

$$y_{ij}^{d,s} \in INT, \quad \forall ij\in MA^{d,s}, d\in GP, s=1\ldots\tau. \tag{21}$$

The objective function (1) minimizes the expected total costs, including the expected operating costs for truck usage and the expected costs for transporting the flood emergency response materials. Note that, as in the DFMDM, the first item, which is zero in this study (refer to the fifth assumption), is retained for a more general form that will be useful for other applications. Constraint (12) ensures the truck-flow conservation for each node for each demand scenario. Constraint (13) ensures the material-flow conservation for each node and ensures that the response requests at each demand node are satisfied for each demand scenario. Constraint (14) ensures that each emergency site can only be serviced by at most one truck per time spot for each demand scenario. Constraint (15) ensures that the total volume transported on a truck cannot exceed the volume capacity of that truck for each demand scenario. Constraint (16) ensures that the total weight to be transported on a truck cannot exceed the weight capacity of that truck for each demand scenario. Constraint (17) is the nonanticipativity constraint that ensures that the amount of flood emergency response materials allocated to a stockpile location is the same for all demand scenarios. Note that because of constraint (17), $y_{ij}^{d,s}$ can be seen as the first stage variables, i.e., for each d, its values for all s (scenarios) are the same. The other variables, i.e., x_{ij}^s are the second stage variables, i.e., for each ij, the value may be different given different s. Constraints (18) and (19) guarantee that all arc flows are within their bounds. Constraints (20) and (21) ensure that all arc flows are integers. Note that a post-optimization analysis may be performed by slightly adjusting the optimization results to more closely correspond to actual practices.

It should be noted that a wait-and-see (WS) solution can be obtained by solving the SFMDM without constraint (17). This solution contains the DFMDM solutions associated with all demand scenarios, but does not require the deployment of flood emergency response materials to a stockpile location to be the same for all demand scenarios. Obviously, the WS solution can serve as a lower bound to the SFMDM solution, which is often called the here-and-now (HN) solution under the stochastic environment. In addition, the expected values of perfect information (EVPI) and the stochastic solution (VSS) can be used to evaluate the HN solution and the performance of the stochastic model, respectively, where EVPI = HN-WS and VSS = EEV-HN [28]. Note that the expected value of the expected value problem (EEV) is obtained by inputting the solution from the deterministic model, with an average demand scenario, into the stochastic model.

3. Solution algorithm

In this section, the solution procedures for both models, the DFMDM and the SFMDM, are outlined. Using the C++ computer language, coupled with CPLEX 11, the DFMDM can be solved within a reasonable time for realistically sized problems. However, it is almost impossible to optimally solve the SFMDM (characterized as strongly NP-hard) within a reasonable period of time for realistic problems. As the complexity of the SFMDM is closely correlated to the number of variables, the solution efficiency can be increased by suitably reducing the number of variables. The problem decomposition technique coupled with the variable fixing technique has been used in past studies to efficiently solve time-space network-based vehicle/crew scheduling problems [25,31], as well as capacitated network design problems [32]. Therefore, we develop a solution algorithm, coupled with CPLEX MIP, to solve the SFMDM, based on the problem decomposition technique coupled with the variable fixing technique.

The solution algorithm for efficiently finding near-optimal solutions for the SFMDM is an iterative two-phase algorithm. The rationale behind this is that, in each iteration, we find the best allocation of flood emergency response materials to a stockpile location and then fix the flow variables associated with that location. In each iteration in phase I, we first find the optimal flood emergency response material allocation as well as the optimal choice for dispatch of trucks to transport these materials to flood emergency sites for each demand scenario. In phase II, from all solutions found for each demand scenario in phase I, we identify the best allocation of materials for a stockpile location, that is, where there is minimal variation in the levels of inventory for all demand scenarios (in terms of the coefficient of variation of the levels of inventory), to determine the suitable quantity of materials to be allocated to that location. Given the subset of locations where the required inventory levels of flood emergency response materials are determined, and when the flow variables associated with the stockpile locations are fixed, we then find another best allocation of materials for a stockpile location, to determine the required quantity of materials to be allocated to that location and to fix the flow variables associated with it. The process is repeated until the amount of flood emergency response materials required at all stockpile locations is determined.

The solution method is described as follows:

1. Initialization: set N (the number of iterations), τ (the number of demand scenarios) and generate the required data for each demand scenario.
2. Set $n = 1$.
3. Set $s = 1$.
4. Solve the associated DFMDM and record the solutions for the associated demand scenario.
5. If $s = \tau$, calculate the variation in the required flood response materials allocated to each stockpile location and go to Step 6; otherwise, $s = s+1$, and return to Step 4.
6. If $n = N$, go to Step 7; otherwise, select the best location for the emergency response materials stockpile (where there is minimal variation in the level of inventory of materials) to determine the required inventory levels to be allocated to that location and fix the associated flow variables; let $n = n+1$ and return to Step 3.
7. Record the flood emergency response material allocation and the dispatching of trucks to transport the materials from stockpile locations to the flood emergency sites and the associated handling cost.

It should be noted that the WS solution can be obtained by taking the expected result of all stochastic scenarios found in Step 4 in the first iteration ($s = 1$). The WS solution is found by solving the SFMDM without the nonanticipativity constraint (17), which can be decomposed into multiple DFMDMs, each associated with a demand scenario. These multiple DFMDMs can then be solved independently. Consequently, the objective value of the WS solution, obtained by taking the expected objective value for all demand scenarios, can serve as a lower bound for the SFMDM solution obtained by the heuristic algorithm. Because of this property, the quality of the SFMDM solution can be evaluated by comparing it with the WS solution.

4. Numerical tests

Numerical tests were conducted using historical data obtained from one of the ten River Management Offices in Taiwan with reasonable simplifications, in order to evaluate how well the models could be applied in the real world. The C++ computer language coupled with CPLEX 11.1 was used to build the models and to solve the problems. The tests were run on an Intel Core i7-2600 CPU 3.4 GHZ desktop computer with 8 GB of RAM in the Microsoft Windows 7 environment.

4.1. Data analysis

The numerical tests refer to a flood emergency response network for the River Management Office. The flood emergency response system is implemented along rivers falling within the jurisdiction of the River Management Office which is in charge to the response to emergency flooding events. There are 8 stockpile locations (denoted as S1, S2, S3, S4, S5, S6, S7, S8) and 8 flood emergency sites (denoted as E1, E2, E3, E4, E5, E6, E7, E8) located in the district as shown in Fig. 3. The distance matrix from the stockpile locations to the flood emergency sites is shown in Table 1. Sand bags can be stored at any stockpile location without a storage capacity constraint. All stockpile locations, except for stockpile 8, have the capacity for storing 1000 2-ton concrete blocks and 600 5-ton concrete blocks. Due to storage space limitations, only sand bags can be stored at stockpile 8. In practice, the response to a flood emergency event must be prompt and effective in order to prevent further damage. Therefore, we assume the duration of the planning period to be one day (24 h). Based on the practices of the River Management Office, the node interval in the network is set to 10 min (i.e., 6 nodes per hour and

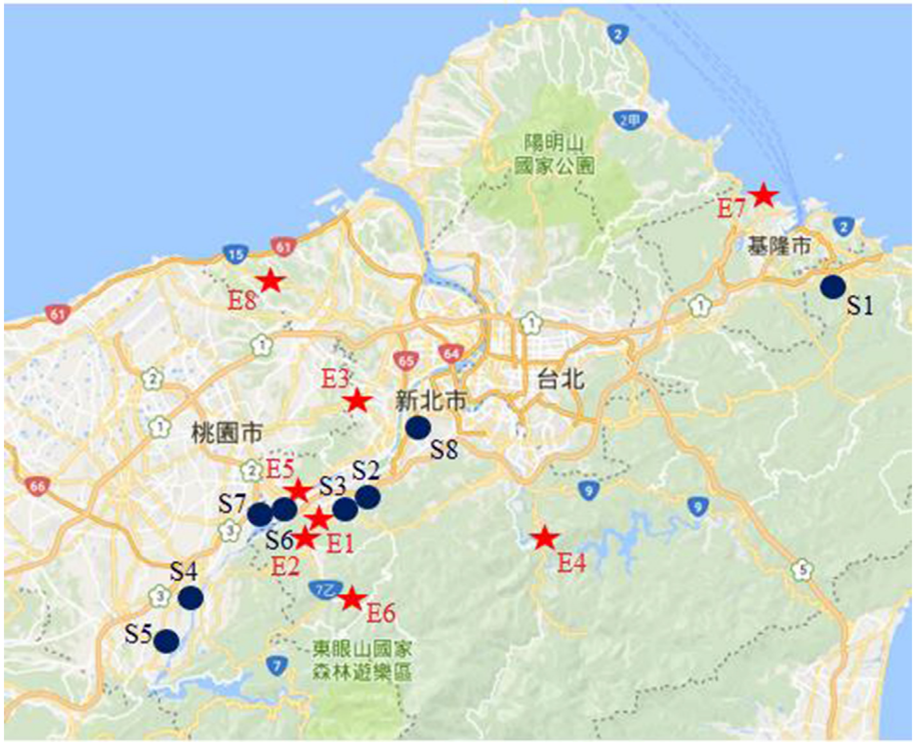

Fig. 3. Site locations for the numerical tests.

144 nodes in total for each location). Information about an emergency flood event includes information about the location of the emergency site and the quantities of materials required to respond to the emergency event. The probability of occurrence and magnitude of possible flood emergency events are estimated based on historical data provided by the River Management Office. After careful investigation, the number of demand scenarios is set to be 120. This will be discussed further in Section 4.2.

In this study, there are three types of flood emergency response materials: 5-ton concrete blocks, 2-ton concrete blocks and sand bags. The configuration and cost parameters associated with the flood emergency response materials as determined by contract are shown in Table 2. The arc costs for distributing these three types of response materials are calculated based on these cost parameters. Only one type of vehicle, 20-ton trucks, is used to transport response materials. The weight and volume capacities of the truck are 10.0 tons and 26.6 cubic meters, respectively. The loading times at the stockpile locations and unloading times at the flood emergency sites may vary depending on the type of material and the site. The loading times at the stockpile locations and unloading times at the flood emergency sites are assumed to be 20 min, a rough average of the required loading and unloading times.

Table 1. The distance matrix from stockpile locations to flood emergency sites (km)

	E1	E2	E3	E4	E5	E6	E7	E8
S1	60.5	61.2	50.1	44.9	60.2	69.4	16.5	55.4
S2	4.3	4.6	14.7	26.8	9.4	12.7	52.9	33.7
S3	3.4	3.8	15.9	28.0	6.4	11.9	54.1	36.4
S4	21.2	14.5	25.8	48.5	15.6	18.7	75.2	43.7
S5	26.0	26.6	36.1	54.5	26.6	25.4	80.6	49.0
S6	4.8	5.3	15.9	33.0	1.9	13.6	59.1	34.4
S7	5.0	5.7	15.1	33.4	2.3	13.9	59.5	34.8
S8	12.2	12.6	7.5	29.3	13.2	20.7	46.6	25.0

Since only three types of response materials are considered, the time-space networks in the DFMDM are comprised of a transport truck-flow network and three response material-flow time-space networks. Since 120 different flood emergency scenarios are considered, there are one hundred and twenty layers in the transport truck-flow time-space networks and three hundred and sixty layers in the material-flow time-space networks for the SFMDM. The test problem sizes of the DFMDM or the SFMDM are large. In the DFMDM, there are 9,172 nodes, 51,410 arcs and 79,150 constraints, in which 51,410 constraints ensure the integrality and bounds of the arc flows, 9,172 constraints ensure flow conservation at each node, and there are 18,568

Table 2. The configuration and cost parameters associated with the response materials

Items	Weight (ton/unit)	Volume (m^3/unit)	Loading and unloading Cost (NTD/unit)	Transportation Cost (NTD/km-unit)	Available Quantity
2-Ton Concrete Blocks (A)	2.0	2.7	672	30	4105
5-Ton Concrete Blocks (B)	5.0	6.1	860	70	3166
Sand Bags (C)	0.11	0.1	420	0	344

Note that there are 10 smaller sand bags in each sand bag unit and each smaller sand bag weighs 0.011 Tons. Because sandbags are significantly lighter than the other two types of material, their transportation cost is set to be zero in the contract.

side constraints. The SFMDM contains 1,110,283 nodes, 6,166,344 arcs and 9,495,144 constraints, in which 6,166,344 constraints guarantee the integrality and bounds of the arc flows, 1,100,640 constraints ensure the flow conservation, and there are also 2,228,160 side constraints.

4.2. Test results

4.2.1. Test results of the deterministic model

Using the C++ computer language, coupled with CPLEX 11, the DFMDM can be solved within 1 s. The optimal objective value of the DFMDM is NTD 318,698, which is the total operating costs for truck usage plus the total cost of delivering the three response materials within the one-day planning horizon. Details of material deployment, truck dispatch and material movements are shown in Tables 3, 4. 2-ton concrete blocks are stored at stockpiles S1, S2, S3, S5, S6, S7 and 5-ton concrete blocks are stored at stockpiles S1, S2, S3, S4, S5, S6, S7. Only sand bags are stored at stockpiles S1, S2, S3, S4, with most of them being stored at stockpile S1. The total number of dispatched trucks is 91, mostly from stockpiles S2 and S3. Details about material movements are shown in Table 5.

Requests for 2-ton and 5-ton concrete blocks are served by stockpile locations closer to the emergency sites. However, sand bags do not need to come from the closest locations, as long as enough material can be transported to fulfill the demand within one day. Thus, the handling cost for sand bags is not related to stockpile location in this study. Thus, 339 sand bag units are stored at S1 (3 units to E1), 3 units at S2 (1 unit to E3, 1 unit to E4, 1 unit to E8), 1 unit at S3 (1 unit to E2) and 1 unit at S4 (1 unit to E7). To ensure that the allocation of stockpile locations closely matches actual practices, a post-optimization analysis may be performed, by slightly adjusting the optimization results without changing the objective. For example, some sand bags may be relocated to stockpile locations that are closer to the emergency sites. Specifically, 337 units are stored at S1 (1 unit to E7), 3 units at S2 (1 unit to E3, 1 unit to E4, 1 unit to E8), and 4 units at S3 (3 units to E1 and 1

Table 3. Detailed inventory levels of response materials at stockpile locations from the DFMDM

Stockpile	1	2	3	4	5	6	7	8
2-Ton Concrete Blocks (A)	1000	35	74	0	996	1000	1000	0
5-Ton Concrete Blocks (B)	600	28	600	138	600	600	600	0
Sand Bags (C)	339	3	1	1	0	0	0	0

Table 4. Detailed transport truck dispatch from the DFMDM

Site	Stockpile							
	S1	S2	S3	S4	S5	S6	S7	S8
E1	1		18					
E2			21					
E3		2						
E4		9						
E5						8		
E6			5					
E7	2			1				
E8		14						
Total	3	25	44	1		8		

Table 5. Detailed response material movements from the DFMDM

Site	Items	Demand	Stockpile							
		(Units)	S1	S2	S3	S4	S5	S6	S7	S8
E1	A	23			23					
	B	25			25					
	C	3	3							
E2	A	48			48					
	B	20			20					
	C	1			1					
E3	A	4		4						
	B	0								
	C	1		1						
E4	A	31		31						
	B	2		2						
	C	1		1						
E5	A	0								
	B	15						15		
	C	0								
E6	A	3			3					
	B	8			8					
	C	0								
E7	A	4	4							
	B	2	2							
	C	1				1				
E8	A	0								
	B	26		26						
	C	1		1						
Total	A	113	4	35	74					
	B	98	2	28	53			15		
	C	8	3	3	1	1				

unit to E2). In another example, 5 of the sand bag units stored at S2, S3 and S4 may be stored at S1. All sand bags (344 units) are thus stored at S1 to simplify operations.

Note that, in the DFMDM, only the minimal required response materials may be stored in each stockpile location (e.g., 2-ton or 5-ton concrete blocks at stockpiles S2 and S3). This may lead to greater transportation costs when more severe flood emergency events occur under stochastic demands requiring more response materials which would have to be transported from other stockpile locations. This result indicates that the SFMDM would be more appropriate than the DFMDM for solving this type of problem.

4.2.2. Test results of the stochastic model

We investigated the most appropriate number of demand scenarios that could suitably represent the demand population, before starting to perform the numerical tests. In our results, we found that after 120 scenarios, the allocation of materials remained almost the same. After 120 scenarios, the objective values changed only slightly, as shown in Fig. 4. Thus, we set the number of demand scenarios to be 120.

Using the C++ computer language, coupled with CPLEX 11, the SFMDM cannot be solved within 20 min for all test instances. The iterative two-phase algorithm is thus used to solve the SFMDM. The optimal objective value of the SFMDM is NTD 320,334, which is the total expected operating cost of truck usage plus the total expected cost of delivering the three response materials within the one-day planning period. The details for material deployment are shown in Table 6. Most of the 2-Ton concrete blocks and the 5-Ton concrete blocks are stored at stockpiles S1, S2, S3, S4, S5, S6 with a few of them stored at S7. These stockpiles with their

Table 6. Detailed inventory levels of response materials at stockpile locations from the SFMDM

Stockpiles	1	2	3	4	5	6	7	8
Item A	834	787	804	815	495	352	18	0
Item B	500	598	523	480	532	445	88	0
Item C	127	0	0	0	0	0	0	217

stored materials are close to emergency sites for different demand scenarios. In addition, sand bags are only stored at stockpiles S1 and S8. Since there is no difference in the handling cost for sand bags from one stockpile to another in this study, in the solution algorithm only stockpiles S1 and S8 are selected for delivering materials to meet the demand within a day. The allocation of materials to these stockpile locations with corresponding material movements is expected to be the optimal one.

We use the expected value of perfect information (EVPI) and the value of the stochastic solution (VSS) to evaluate the performance of the stochastic model and the iterative two-phase algorithm. Table 7 shows the results of these two evaluations. The EVPI for the SFMDM is about NTD 111, meaning that the maximum error gap of the HN solution is only 0.03% (=111/320223). This shows that the solution obtained by the solution algorithm is very close to the optimal solution, indicating the effectiveness of the solution algorithm. The VSS is used to measure the value of using a stochastic model. The VSS for the SFMDM is NTD 8,345, meaning that the gap is 2.61% (=8345/320334) for the SFMDM. This indicates that it is suitable to use the SFMDM to solve the problem.

4.3. Comparison

We now compare the performance of the DFMDM, the SFMDM, and actual deployment practices currently used by the River Management

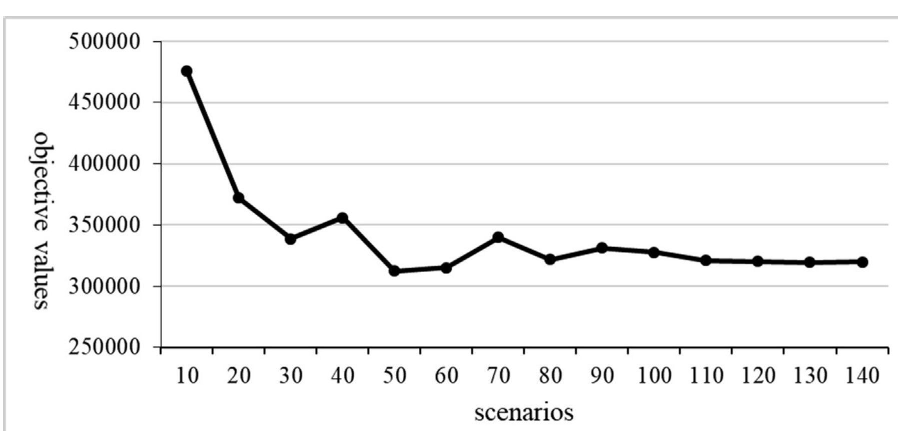

Fig. 4. The objective values for different numbers of demand scenarios.

Table 7. Evaluation of the SFMDM solutions

HN (SFMDM)	WS	EVPI (HN-WS)	EEV	VSS = |EEV-HN|	Error Gap (EVPI/WS)	Gap (VSS/HN)
320,334	320,223	111	328,679	8,345	0.03%	2.61%

Table 8. Comparison of the deployment methods in the planning stage and in the evaluation stage

Year	Planning Stage			Evaluation Stage		
	Practice	DFMDM	SFMDM	Practice	DFMDM	SFMDM
1	323,423	318,698	321,060	330,014	355,867	321,060
2	323,423	318,698	320,648	330,556	333,690	320,648
3	325,268	318,698	321,132	342,563	328,679	321,132
4	320,963	318,698	320,223	324,477	328,679	320,223
5	321,043	318,698	320,334	327,982	328,679	320,334

Office for real world operations. We first randomly generate 120 demand scenarios based on the demands in the DFMDM then calculate the actual handling costs for five-years of operations (years 1–5). Table 8 shows the comparison results. Although the objective values obtained with the DFMDM are the smallest among the three deployment methods, this does not mean that its performance is better than that of the SFMDM. Indeed, it is necessary to evaluate the performance of these deployment methods after their application to actual operations rather than in the planning state. As shown in Table 8, the evaluation results indicate that the SFMDM yields the best solution, regardless of the evaluation year. On average, the current deployment practices are next while the DFMDM performs the worst. In the evaluation stage, the actual handling cost of the DFMDM is greater than that of the SFMDM because when applied to real world operations, the SFMDM deployment can better absorb stochastic demand disturbances than can the DFMDM. Although the DFMDM yields the best solution in the planning stage, it distributes resources too tightly to be easily adjusted to cope with the stochastic demand disturbances that occur. As a result, in real world operations where stochastic demands do occur, the SFMDM should be more effective for modeling the deployment of resources for flood emergency response than the DFMDM or current deployment practices.

5. Conclusions

In this study, we adopt a time-space network technique to formulate two flood emergency response material allocation models (DFMDM and SFMDM) to determine the flood emergency response material deployment, truck routing and flood emergency response material delivery from stockpile locations to flood emergency sites. A deterministic deployment model (DFMDM) for flood emergency response material systems is first developed followed by a stochastic deployment model (SFMDM) to deal with the issue of uncertain demands. Both models are formulated as multiple integer network flow problems with special side constraints. An iterative two-phase solution algorithm is developed based on a problem decomposition technique, coupled with a variable fixing technique, to efficiently solve the SFMDM. To evaluate the proposed models and solution algorithm, numerical tests are performed. The test results, related to a Taiwan flood emergency response system, are shown to compare favorably with current practices, demonstrating the potential usefulness of the stochastic deployment model in practice. More tests are suggested before application of the proposed stochastic mode and solution algorithm before being used in real operations, so that its characteristics and limitations can be grasped. In future, modification of the SFMDM, coupled with the solution algorithm, to consider multiple truck types can be researched. Besides, how to modify the DFMDM to be used for the contractor can be researched as well.

Declaration of interest

The authors declare no conflict of interest.

Acknowledgements

This research was partially supported by grants (MOST-110-2221-E-008-025-MY3) and MOST-110-2221-E-008-026 and from the Ministry of Science and Technology, Taiwan. The authors would like to thank the River Management Office for kindly providing the test data and their valuable opinions. Finally, the authors thank two reviewers for their helpful comments and suggestions to improve the presentation of the paper.

References

[1] Ministry of the Interior. Taiwan, Taipei: National Fire Agency Annual Report; 2015.
[2] Gilvear DJ, Davies JR, Winterbottom SJ. Mechanisms of floodbank failure during large flood events on the rivers Tay and Earn, Scotland. Q J Eng Geol Hydrogeol 1994;27(4): 319–32.
[3] Chang MS, Tseng YL, Chen JW. A scenario planning approach for the flood emergency logistics preparation problem under uncertainty. Transport Res E Logist Transport Rev 2007;43(6):737–54.

[4] Chiu YC, Zheng H. Real-time mobilization decisions for multi-priority emergency response resources and evacuation groups: model formulation and solution. Transport Res E Logist Transport Rev 2007;43(6):710–36.
[5] Li S, Teo KL. Post-disaster multi-period road network repair: work scheduling and relief logistics optimization. Ann Oper Res 2019;283:1345–85.
[6] Özdamar L, Demir O. A hierarchical clustering and routing procedure for large scale disaster relief logistics planning. Transport Res E Logist Transport Rev 2012;48(3):591–602.
[7] Al Theeb N, Murray C. Vehicle routing and resource distribution in postdisaster humanitarian relief operations. Int Trans Oper Res 2016;24(6):1253–84.
[8] Rawls CG, Turnquist MA. Pre-positioning and dynamic delivery planning for short-term response following a natural disaster. Soc Econ Plann Sci 2012;46(1):46–54.
[9] Verma A, Gaukler GM. Pre-positioning disaster response facilities at safe locations: an evaluation of deterministic and stochastic modeling approaches. Comput Oper Res 2015;62:197–209.
[10] Garrido RA, Lamas P, Pino FJ. A stochastic programming approach for floods emergency logistics. Transport Res E Logist Transport Rev 2015;75:18–31.
[11] Galindo G, Batta R. Review of recent developments in OR/MS research in disaster operations management. Eur J Oper Res 2013;230(2):201–11.
[12] Anaya-Arenas AM, Renaud J, Ruiz A. Relief distribution networks: a systematic review. Ann Oper Res 2014;223(1):53–79.
[13] Özdamar L. Planning helicopter logistics in disaster relief. Spectrum 2011;33(3):655–72.
[14] Bozorgi-Amiri A, Jabalameli MS, Al-e-Hashem SMJM. A multi-objective robust stochastic programming model for disaster relief logistics under uncertainty. Spectrum 2013;35(4):905–33.
[15] Matisziw TC, Murray AT. Modeling s–t path availability to support disaster vulnerability assessment of network infrastructure. Comput Oper Res 2009;36(1):16–26.
[16] Duque PM, Sörensen K. A GRASP metaheuristic to improve accessibility after a disaster. Spectrum 2011;33(3):525–42.
[17] Yan S, Shih YL. An ant colony system-based hybrid algorithm for an emergency roadway repair time-space network flow problem. Transportmetrica 2012;8(5):361–86.
[18] Yan S, Chu JC, Shih YL. Optimal scheduling for highway emergency repairs under large-scale supply–demand perturbations. IEEE Trans Intell Transport Syst 2014;15(6):2378–93.
[19] Aksu DT, Özdamar L. A mathematical model for post-disaster road restoration: enabling accessibility and evacuation. Transport Res E Logist Transport Rev 2014;61:56–67.
[20] Paciarotti C, Cesaroni A, Bevilacqua M. The management of spontaneous volunteers: a successful model from a flood emergency in Italy. Int J Disaster Risk Reduc 2018;31:260–74.
[21] Lu M, Liao X, Yue H, Huang Y, Ye H, Xu C, et al. Optimizing distribution of droneports for emergency monitoring of flood disasters in China. J Flood Risk Manag 2020;13(1):e12593.
[22] Lin A, Wu H, Liang G, Cardenas-Tristan A, Wu X, Zhao C, et al. A big data-driven dynamic estimation model of relief supplies demand in urban flood disaster. Int J Disaster Risk Reduc 2020;49:101682.
[23] Hsu CI, Hsieh YP. Direct versus terminal routing on a maritime hub-and-spoke container network. J Marine Sci Techn- Taiwan 2005;13(3):209–17.
[24] Yan S, Chen CH, Chen HY, Lou TC. Optimal scheduling models for ferry companies under alliances. J Marine Sci Techn- Taiwan 2007;15(1):53–66.
[25] Steinzen I, Gintner V, Suhl L, Kliewer N. A time-space network approach for the integrated vehicle-and crew-scheduling problem with multiple depots. Transport Sci 2010;44:367–82.
[26] Chu JC, Yan S, Huang HJ. A multi-trip split delivery vehicle routing problem with time windows for inventory replenishment under stochastic travel times. Network Spatial Econ 2017;17:41–68.
[27] Higle JL, Sen S. Stochastic decomposition. Dordrecht: Kluwer Academic publishers; 1996.
[28] Birge JR, Louveaux F. Introduction to stochastic programming. New York: Springer-Verlag; 1997.
[29] Ruszczynski A, Shapiro A. Stochastic programming. Amsterdam: Elsevier; 2003.
[30] Yan S, Chi CJ, Tang CH. Inter-city bus routing and timetable setting under stochastic demands. Transport Res Part A 2006;40:572–86.
[31] Lu CC, Yan S, Ko HC, Chen HJ. A bilevel model with a solution algorithm for locating weigh-in-motion stations. IEEE Trans Intell Transport Syst 2018;19(2):380–9.
[32] Holmberg K, Yuan D. A Lagrangian heuristic based branch-and-bound approach for the capacitated network design problem. Oper Res 2000;48:461–81.