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IMPROVING EVACUATION PLANNING AND SHELTER SITE SELECTION FOR FLOOD DISASTER: THAI FLOODING CASE STUDY

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Evacuation planning and shelter site selection are the most important function of disaster management for the purpose of helping at-risk persons to avoid or recover from the effect of a disaster. This study aims to propose a stochastic linear mixed-integer mathematical programming model for improving flood evacuation planning and shelter site selection under a hierarchical evacuation concept. The hierarchical evacuation concept is applied in this study that balances the preparedness and risk despite the uncertainties of flood events. This study considers the distribution of shelter sites and communities, evacuee's behavior, utilization of shelter and capacity restrictions of the shelter by minimizing total population-weighted travel distance. We conduct computational experiments to illustrate how the proposed methodical model works on a real case problem in which we proposed Thai flooding case study. Also, we perform a sensitivity analysis on the parameters of the mentioned mathematical model and discuss our finding. This study will be a great significance in helping policymakers consider the spatial aspect of the strategic placement of flood shelters and evacuation planning under uncertainties of flood scenarios.

Key Words : *stochastic programming, shelter site selection, evacuation planning, flood disaster*

1. INTRODUCTION

Recently, the world has affected by many disasters such as earthquakes, storms, floods, landslides, etc. Since the 1950s, the number of disasters has been continuously increasing, as shown in **Fig.1**[1)]. According to the international disaster database, they propose that Asia and America are the most affected continues by natural disasters such as hydrological disaster, geophysical disaster, meteorological disaster, climatological disaster[2)]. The World Health Organization (WHO) defines a 'disaster' as any occurrence that causes damage, destruction, ecological disruption, loss of human life, human suffering, deterioration of health and health services on a scale sufficient to warrant an extraordinary response from outside the affected community or area[3)]. Owing to the increasing severity of recent of disasters, academicians have paid a great deal of attention to "Disaster Management" for the purposes of helping at-risk persons to avoid or recover from the effects of a disaster. The activity of disaster management consists of four stages: mitigation, preparation, response, and recovery[4), 5)].

Flood disaster is the largest share of natural disaster occurrence in 2014 to estimate to be 47.2% (**Fig. 2**). The number of floods and mass movement of hydrological origin were 153 disasters in 2014. The massive flood disaster occurred in China and Thailand in 2011. Flood shelter site selection and flood evacuation planning are a major activity that should prepare and plan before the floods occur in order to help people in an affected zone to avoid from the effect of the flood disaster. In flood shelter site selection and flood evacuation planning, there are many major criteria that should be considered such as evacuation distance, uncertainty of occurrence, evacuee's behavior, utilization of shelter and hazard of flood disaster. Our previous model proposed solutions for evacuation planning and shelter site selection which

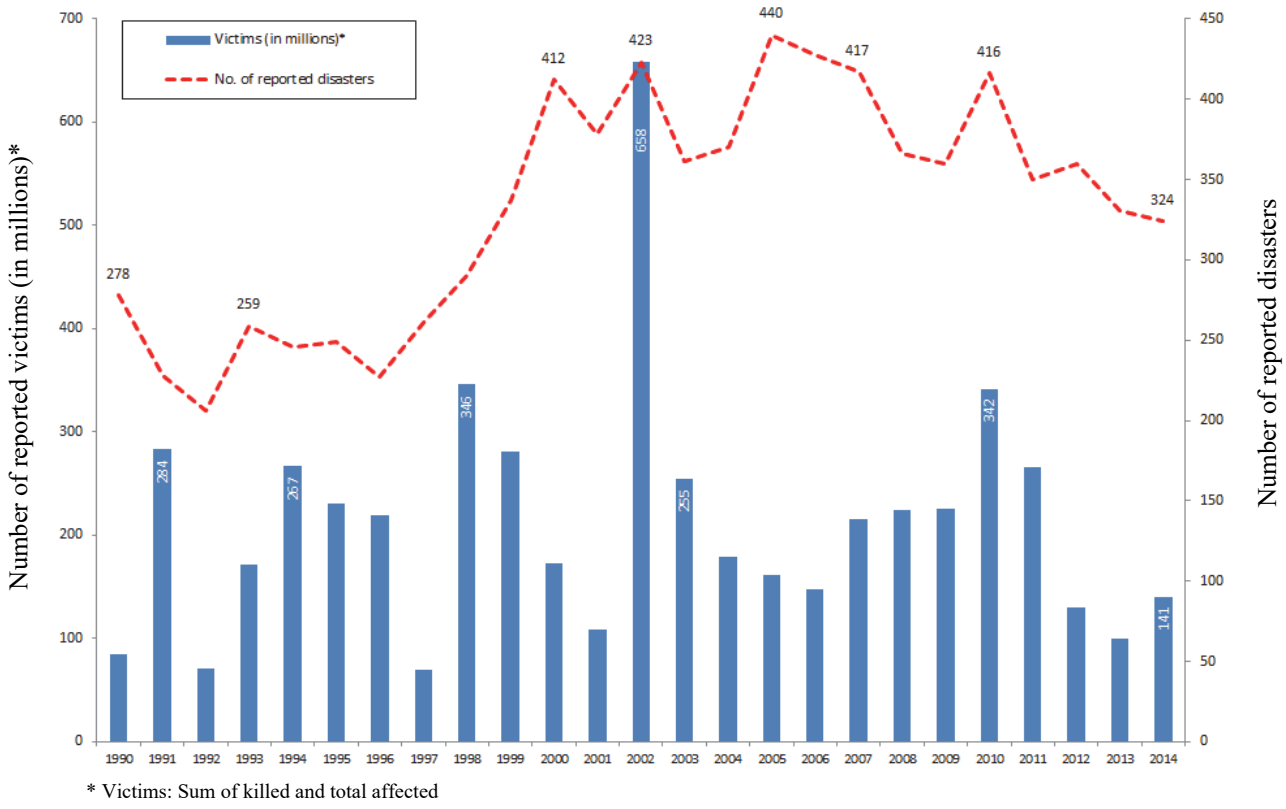


Fig. 1 Trends in occurrence and victims[1)].

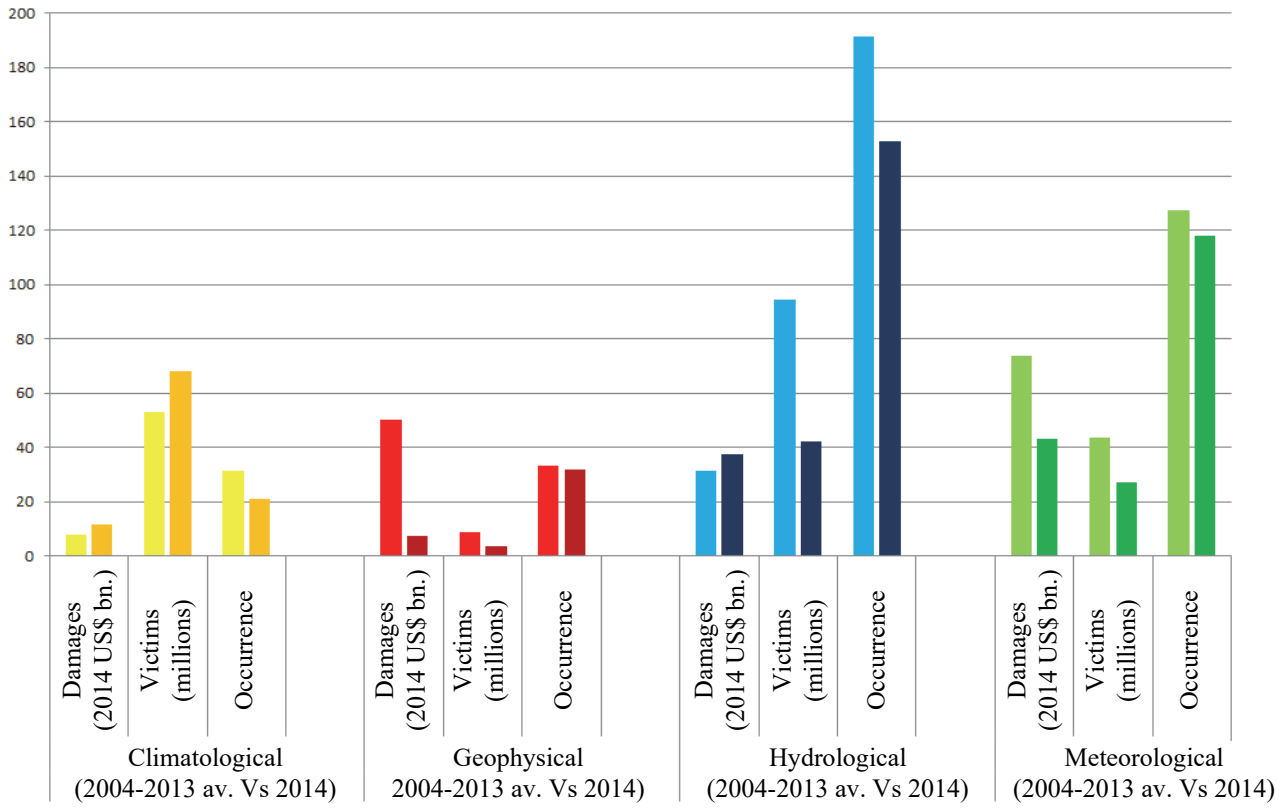


Fig. 2 Natural disaster impacts by disaster sub-group: 2014 versus 2003-2013 annual average[1)].

considers the assignment of communities and evacuee's behavior condition[5]. However, that model is lacking some major criteria that should be considered such as utilization of shelter. Therefore, we aim to develop that model for designing flood shelter site selection and flood evacuation planning under probabilistic scenarios that reflect the uncertainties of flood events and their consequences in which this study aims to consider the distribution of shelter sites and communities, evacuee's behavior, utilization of shelter and capacity restrictions of shelter simultaneously.

The remainder of this study is organized as follows: Section 2 presents a review of related literature. Section 3 shows conceptual model and mathematical model. To illustrate how the proposed mathematical model works on the real case, we propose the case study in section 4. Section 5 shows the computational results and sensitivity analysis. Finally, the conclusion and discussions are presented in Section 6.

2. LITERATURE REVIEWS

This section presents an overview of relevant literature. Recent research has also included surveys on effective DM such as Caunhyeet al.[6], and Özdamar and Ertem[7], Boonmee et al.[8] and Zheng et al.[9]. There are many papers dealing with sheltering operation and evacuation planning. **Table 1** displays important characteristics of existing studies in this area comprising of objective function, time period horizon, category of single or multistage approach, category of deterministic or stochastic programming, mathematical model, solutions algorithms and case study.

Chanta and Sungsawang[10] proposed bi-objective optimization model to select temporary shelter sites for flood disaster in Bangkruai, Thailand. The objective functions aim to maximize the number of victims that can be covered within a fixed distance and to minimize the total distance of all victims to their closest shelters. Boonmee et al.[11] proposed multi-model optimization for shelter site selection and evacuation planning. The mathematical models were formulated under different constraints and model types. The objective function is to minimize the total travel distance. Finally, all models were proposed to policymakers for choosing the best evacuation plan. Chowdhury et al.[12] proposed multi-objective mathematical programming model and simulation model to quantify objectives and provided decision support for cyclone shelter location in Bangladesh. Santos et al.[13] proposed a maximal covering location problems (MCLP) with Lagrange optimization model for flood shelter site selection. The proposed mathematical model aims to maximize the population covered by the limited number of facility locations. Moreover, this study also considers flood level constraint. Similarly, Wang et al.[14] proposed an MCLP-based optimization model to identify the best precipitation stations. The proposed model considers some special constraints and the associated rainfall monitoring demand. This study was applied in Jinsha River Basin. Kulshrestha et al.[15] presented a robust shelter location model to determine optimal shelter locations and their capacities under demand uncertainty. This proposed model not only determines the number of shelters and capacities but also considers the route to access to shelters. Kongsomsaksakul et al.[16] studied shelter location-allocation model for flood evacuation planning. The mathematical model was formulated as a bi-level programming model. The upper bound is a location problem while the lower bound is a combined distribution and assignment (CDA) model. The proposed model was solved by using a genetic algorithm. Addition, bi-level programming model was proposed by Li et al.[17] for developing dynamic traffic assignment problem for the selection of shelter locations with explicit consideration of a range of possible hurricane events and the evacuation needs under each of those events. Others bi-level programming model was proposed by Liu et al.[18] and Feng and Wen[19].

Stochastic programming is one of the most widely used approaches for planning in evacuation planning and shelter site selection due to its ability to account for uncertain criteria. Salmam and Yücel[20] proposed a stochastic integer programming model for determining the location of emergency response facilities among a set of potential ones. The objective aims to maximize the expected total demand covered within a predetermined distance parameter, over all possible network realizations. Furthermore, the stochastic programming in this field is proposed by Mirzapour et al.[21]. This study presents a mixed integer nonlinear programming model of a capacitated facility location-allocation problem which simultaneously considers the probabilistic distribution of demand locations and a fixed line barrier in a region. For integrated decision shelter site selection and evacuation planning under hierarchical evacuation concept, Chen et al.[22] proposed a hierarchical location model for earthquake-shelter planning. This proposed mathematical model considers financial constraints imposed upon the construction of shelters and changing needs of refugees. The real case in Beijing, China is applied to validate this proposed model. Another multi-step evacuation is proposed by Hu et al.[23]. The proposed mixed-integer linear program model is formulated for multi-step evacuation and temporary resettlement under minimization of panic-induced psy-

Table 1 The review study of optimization model on shelter site selection and evacuation planning.

No	Author	Objective	Period	Level	D/S	Math model	Solution	Case study
1	Chanta and Sungsawang[10]	Min distance, Max covering demand	Single	Single	D	Linear	Epsilon constraint	Bangkruai, Thailand
2	Boonmee et al.[11]	Min distance	Single, Multi	Single	D/S	Linear/ Non-Linear	Exact algorithm	Banta, Thailand
3	Chowdhury et al.[12]	Min risk, Min cost, Max protection of units	Single	Single	D	Non-Linear	Greedy heuristic	Bangladesh
4	Santos et al.[13]	Max covering demand	Single	Single	D	Linear	Exact algorithm	Marikina, Philippine
5	Wang et al.[14]	Max covering demand	Single	Single	D	Linear	Exact algorithm	Jinsha River Basin
6	Kulshrestha et al.[15]	Min cost	Single	Single	D	Linear	A cutting-plane algorithm	the Sioux Falls network
7	Kongsomsaksakul et al.[16]	Min evacuation time	Single	Bi	D	Non-Linear	Genetic Algorithm	Utah
8	Li et al.[17]	Min travel time	Multi	Bi	S	Non-Linear	Lagrangian relaxation algorithm	North Carolina
9	Liu et al[18]	Max throughput, Min total trip time	Multi	Bi	D	Linear	Exact algorithm	Ocean City
10	Feng and Wen[19]	Max number of vehicles	Single	Bi	D	Linear	Genetic Algorithm	Numerical example
11	Salmam and Yücel[20]	Max satisfied demand	Single	Single	S	Linear	Tabu search	Istanbul's earthquake preparedness
12	Mirzapour et al.[21]	Min maximum weighted distance	Single	Single	S	Non-Linear	Exact algorithm	Mazandaran province, northern part of Iran
13	Chen et al.[22]	Min weighted distance	Multi	Single	D	Linear	Exact algorithm	Beijing, China
14	Hu et al.[23]	Min cost	Multi	Single	D	Linear	Exact algorithm	Sichuan, China

Note: D = Deterministic problems, S = Stochastic problems

chological penalty cost, psychological intervention cost, and costs associated with transportation and building shelters.

According to the related existing literature review in flood evacuation planning is lacking a determined perspective on the uncertainty of occurrence, evacuee's behavior, utilization of shelter, capacity restriction of shelter, and hierarchical evacuation concept simultaneously. Therefore, our study aims to propose stochastic linear mixed-integer programming model for optimizing integrated decision related to shelter site selection under a hierarchical evacuation concept during flood disaster. This proposed model not only provides a flood shelter site but also considers hierarchical evacuation concept for flood disaster that balances the preparedness and risk despite the uncertainties of flood events. Besides, we consider the distribution of shelter sites and communities, evacuee's behavior, utilization of shelter, and capacity restrictions of shelter as well.

3. THE PROPOSED MODEL

(1) Conceptual model

In this section, we describe the conceptual model for the flood shelter site selection and flood evacuation planning. This conceptual model is designed with respect to the hierarchical evacuation concept. In this study, we assume that each evacuation step is called "Evacuation period". The evacuation periods are provided by the local government or policy makers that can be separated with respect to the step of flooding or the step of impact level from hazard map.

For example, in **Fig. 3** and **4**, we represent three-level hierarchical evacuation model that consists of three evacuation periods and three impact levels. In the 1st evacuation period, when the flood warning system alarms for the 1st evacuation, the refugees who stay in impact level 1 will be assigned to one of the nearby shelters. In the 2nd evacuation period, when the flood warning system alarms for the 2nd evacuation, the refugees who stay in impact level 2 will be assigned to the nearby shelters. While the refugees of selected shelters in the 1st evacuation period where locate in impact level 2, they will be relocated to new shelters. In the 3rd evacuation period, when the flood warning system alarms for the 3rd evacuation, the refugees who stay in impact level 3 will be evacuated to one of the nearby shelters. While the refugees of selected shelters in the 1st evacuation period and the 2nd evacuation period where locate in impact level 3, they will be relocated to the new shelters as well. Before the mathematical model is formulated, we make the following assumptions on the problem:

1. According to evacuee's behavior during flood events, some refugees always evacuate neither before the disaster or after the disaster. Consequently, we assume that the refugees can evacuate to shelter any evacuation periods under varying needs of the refugees.
2. The affected community can be served by one shelter in each period.
3. Some shelter can be located in flooding risk area.
4. Shelters have a limited capacity for accommodating the demand assigned to them.
5. The flood warning system will alarm following the step of impact level with respect to decision making's local government or policymakers.
6. The road network is not considered in this model.

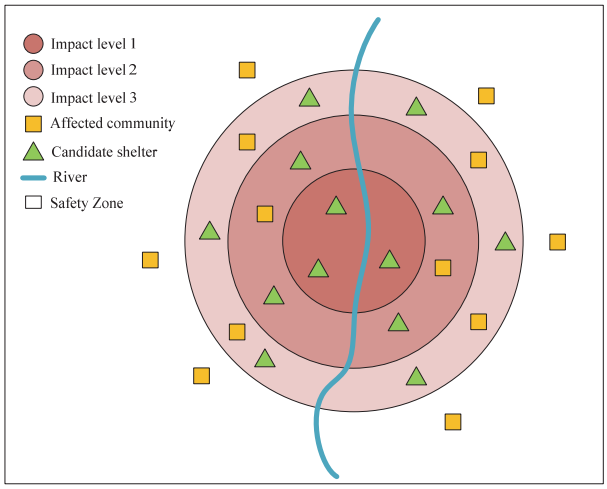


Fig. 3 The hazard map of conceptual model for hierarchical evacuation planning and shelter site selection during floods.

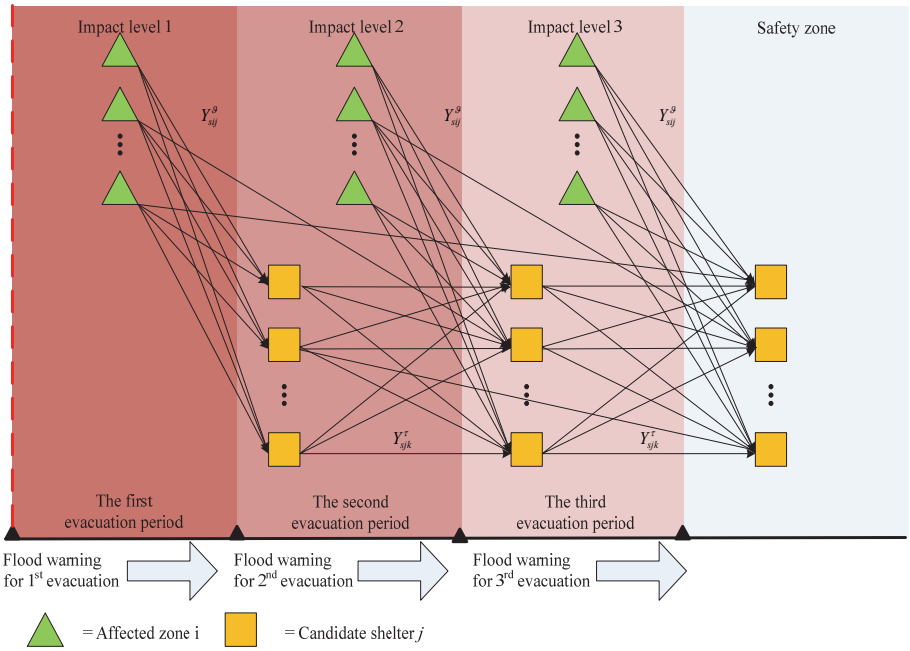


Fig. 4 The conceptual model of for hierarchical evacuation planning and shelter site selection during floods.

(2) Mathematical model

In this section, we proposed the stochastic linear mixed-integer programming model for optimizing integrated decision related to shelter site selection under a hierarchical evacuation concept. The indices, parameters, decision variables, objective function, and constraints are presented as follows:

Indices and index sets

I Set of affected communities; $i \in I$

J Set of candidate shelters; $j, k \in J$

ξ Set of evacuation periods and impact level; $s \in \xi$

Parameters

MS Maximum limit of selected shelters

M A Large positive number

μ Threshold value for minimum utilization of shelter

P_s Probability of flooding in impact level $s \in \xi$

D_i Population in affected community $i \in I$

PD_{si} Proportion of population in affected community $i \in I$ need to evacuate in evacuation period $s \in \xi$

η_j Capacity of shelter $j \in J$

∂_{sj} Equal to 1 if candidate shelter $j \in J$ locate in impact level $s \in \xi$, 0 otherwise

$D(\vartheta)_{ij}$ Distance from affected community $i \in I$ to candidate shelter $j \in J$ (km)

$D(\tau)_{jk}$ Distance from candidate shelter $j \in J$ to candidate shelter $k \in J$ (km)

Decision variables

X_j 1 if shelter $j \in J$ is selected, 0 otherwise

TP_{sj} Total population of shelter $j \in J$ in evacuation period $s \in \xi$

$Y(\vartheta)_{sij}$ 1 if affected community $i \in I$ is assigned to candidate shelter $j \in J$ during evacuation period $s \in \xi$, 0 otherwise

$Y(\tau)_{sjk}$ 1 if shelter $j \in J$ is assigned to candidate shelter $k \in J$ during evacuation period $s \in \xi$, 0 otherwise

$Z(\vartheta)_{sij}$ Number of people evacuates from affected community $i \in I$ to shelter $j \in J$ during evacuation period $s \in \xi$

$Z(\tau)_{sjk}$ Number of people evacuates from affected shelter $j \in J$ to candidate shelter $k \in J$ during evacuation period $s \in \xi$

Objective function

Most evacuation models measure the efficiency of evacuation by total travel cost in terms of response distance or time[24]. Due to the floods typically are known about several hours before communities will be affected, evacuees will have sufficient time for evacuation. Thus, this study aims to focus on travel distance criterion with respect to the population of each community. This objective function is multiple values between population-weighted travel distance and the probability of flooding in each impact level with respect to a disaster scenario. The objective function can be formulated as Equation (1). The expected population-weighted travel distance is expressed in Equation (2), where, this consists of the distance between affected community to shelter and the distance between shelter to shelter as shown in Equation (3).

$$\text{Min } Z \quad E_{\xi}[Q(X_j, s)] \tag{1}$$

$$E_{\xi}[Q(X_j, s)] = \sum_{s \in \xi} P_s * Q(X_j, s) \tag{2}$$

$$Q(X_j, s) = \left\{ \left[\sum_{i \in I} \sum_{j \in J} D(\vartheta)_{ij} * Z(\vartheta)_{sij} \right] + \left[\sum_{j \in J} \sum_{k \in J} D(\tau)_{jk} * Z(\tau)_{sjk} \right] \right\} \quad \forall s \tag{3}$$

Constraints

Maximum number of selected shelters: Equation (4) states that the total number of selected shelters cannot exceed the maximum limit of selected shelter. Equation (5) guarantees that the population can be served to shelter when it is selected.

$$\sum_{j \in J} X_j \le MS \tag{4}$$

$$\sum_{s \in \xi} TP_{sj} \ge X_j \quad \forall j \tag{5}$$

Shelter capacity: Equation (6) states that the total number of evacuees is covered by shelter j should not exceed its capacity.

$$\sum_{s \in \xi} TP_{sj} \ge X_j * \eta_j \quad \forall j \tag{6}$$

Total population in each evacuation periods: Equation (7) states that the total number of population in each evacuation period.

$$\sum_{i \in I} Z(\vartheta)_{sij} * (1 - \partial_{sj}) + \sum_{k \in J} Z(\tau)_{sjk} * (1 - \partial_{sj}) = TP_{sj} \quad \forall j, s \tag{7}$$

Evacuation requirements: Equation (8) ensures that the number of evacuees needs to evacuate to a shelter in each evacuation period should be equal to the expected evacuation requirements with respect to the evacuee's behavior.

$$\sum_{j \in J} Z(\vartheta)_{sij} * (1 - \partial_{sj}) = PD_{si} * D_i \quad \forall i, s \tag{8}$$

Flow balance: Equation (9) and (10) states the balance constraint in which the number of population departure should be equal to the number of the population come. Note that ∂_{sj} present assignment protection for shelters, when the shelter is located in safety

zone, the population does not need to evacuate to a new shelter.

$$TP_{1,j} * \partial_{2,j} = \sum_{k \in J} Z(\tau)_{2,jk} * (1 - \partial_{2,k}) \quad \forall j \qquad (9)$$

$$(TP_{2,j} * \partial_{3,j}) + (TP_{1,j} * (\partial_{3,j} - \partial_{2,j})) = \sum_{k \in J} Z(\tau)_{3,jk} * (1 - \partial_{3,k}) \quad \forall j \qquad (10)$$

Controls the utilization of selected shelter areas: Equation (11) states that if a shelter site is open, then the utilization of that shelter area needs to exceed the pre-determined threshold value. Note that the utilization is a ratio between the number of evacuees is covered and shelter capacity.

$$\sum_{s \in \xi} \frac{TP_{sj}}{\eta_j} \geq \mu * X_j \quad \forall j \qquad (11)$$

Assignment limit: Equation (12) - (13) state that the binary variable of the assignment is set to 1 when the people in each community or each shelter is assigned to each shelter. Equation (14) - (15) ensure that the affected community can be served by one shelter in each period.

$$Z(\vartheta)_{sij} \leq M * Y(\vartheta)_{sij} \quad \forall i,j,s \qquad (12)$$

$$Z(\tau)_{sjk} \leq M * Y(\tau)_{sjk} \quad \forall j,k,s \qquad (13)$$

$$\sum_{j \in J} Y(\vartheta)_{sij} \leq 1 \quad \forall i,s \qquad (14)$$

$$\sum_{k \in J} Y(\tau)_{sjk} \leq 1 \quad \forall j,s \qquad (15)$$

Non-negativity and binary conditions: Equation (16) and (17) describe non-negativity and binary conditions of the decision variable.

$$X_j, Y(\vartheta)_{sij}, Y(\tau)_{sjk} \in \{0,1\} \quad \forall i,j,k,s \qquad (16)$$

$$Z(\vartheta)_{sij}, Z(\tau)_{sjk} \geq 0 \quad \forall i,j,k,s \qquad (17)$$

4. CASE STUDY

To show how the proposed mathematical model can work on the real case problem, this section presents a case study in Chiang Mai province in northern Thailand to validate our proposed model. Chiang Mai Province usually occurs flood disaster in May-October rainy season which is dominated by masses of moist air moving from the Indian Ocean, and tropical depressions moving westward from the South China Sea.

Chiang Mai province develops a flood warning system for Ping river which can predict the real-time situation. This system uses two gauging stations, P.67 located at Ban Mae-tae in Sansai district and P.1 in downtown Chiang Mai, in which the water takes about seven hours for traveling to P.1 station (**Fig. 5**). The Natural Disaster Research Unit of Civil Engineering Department of Chiang Mai University (CENDRU) has surveyed and collected floods data in Chiang Mai for a long time ago[25]. The Chiang Mai flood hazard map is produced based on historical data from Station P.1 and P.67 since 2006 as shown in **Fig 6**, the risk area is divided into seven levels.

According to the classification of the impact level by CENDRU. To apply to our conceptual model, if we determine with respect to seven impact levels, it is too many for evacuation in each level and burdensome for evacuees, especially the evacuees in the first level might have to evacuate several times. So, we assume that the seven impact levels are classified into three impact levels, it implies that we have three evacuation periods. Based on historical data, we can assume that the probability of three impact levels is 0.73, 0.25, and 0.02, respectively[26] as shown in **Table 2**. In this study, we consider 123 communities and 43 candidate shelters, as shown in **Fig. 7**. Unlike other evacuation, the evacuee's behavior during flood disaster is uncertain, someone needs to evacuate after they hear alarm immediately, but someone needs to evacuate when the disaster strike. Hence, evacuee's behavior should be determined. The proportion of the population that needs to evacuate in each evacuation period is referred from Lauthep et al., 44.81% evacuate immediately after warning signal given by the local government, 8.00% evacuate when the flood level is lower than 0.5 meter, and 4.44% evacuate when the flood level is over than 0.5

Table 2 Classification of level for hierarchical evacuation model.

Impact level and evacuation period	1	2	3
Probability	0.73	0.25	0.02
Ping river at P.1 (m)	3.7-4.1	4.1-4.6	Over 4.6
No. affected communities	18	47	123

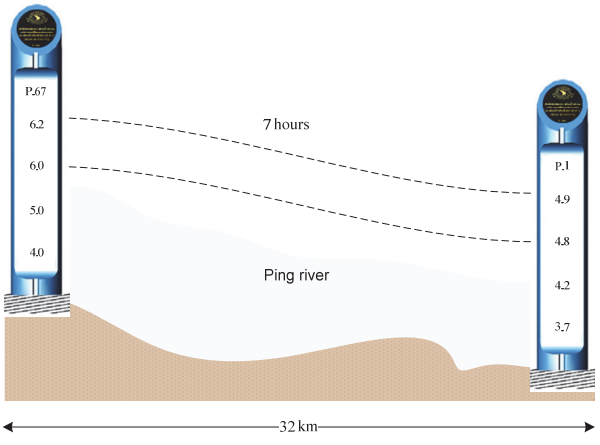


Fig. 5 The position of station P.1 and P.67 on the Ping river.

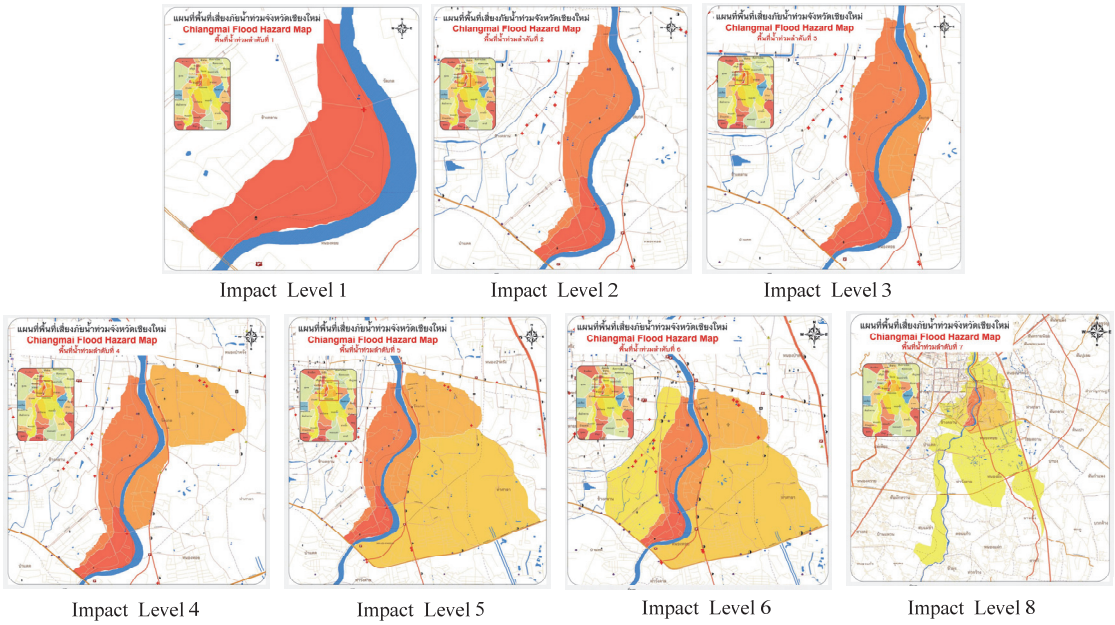


Fig. 6 Seven impact levels of the Chiang Mai flood hazard map[25].

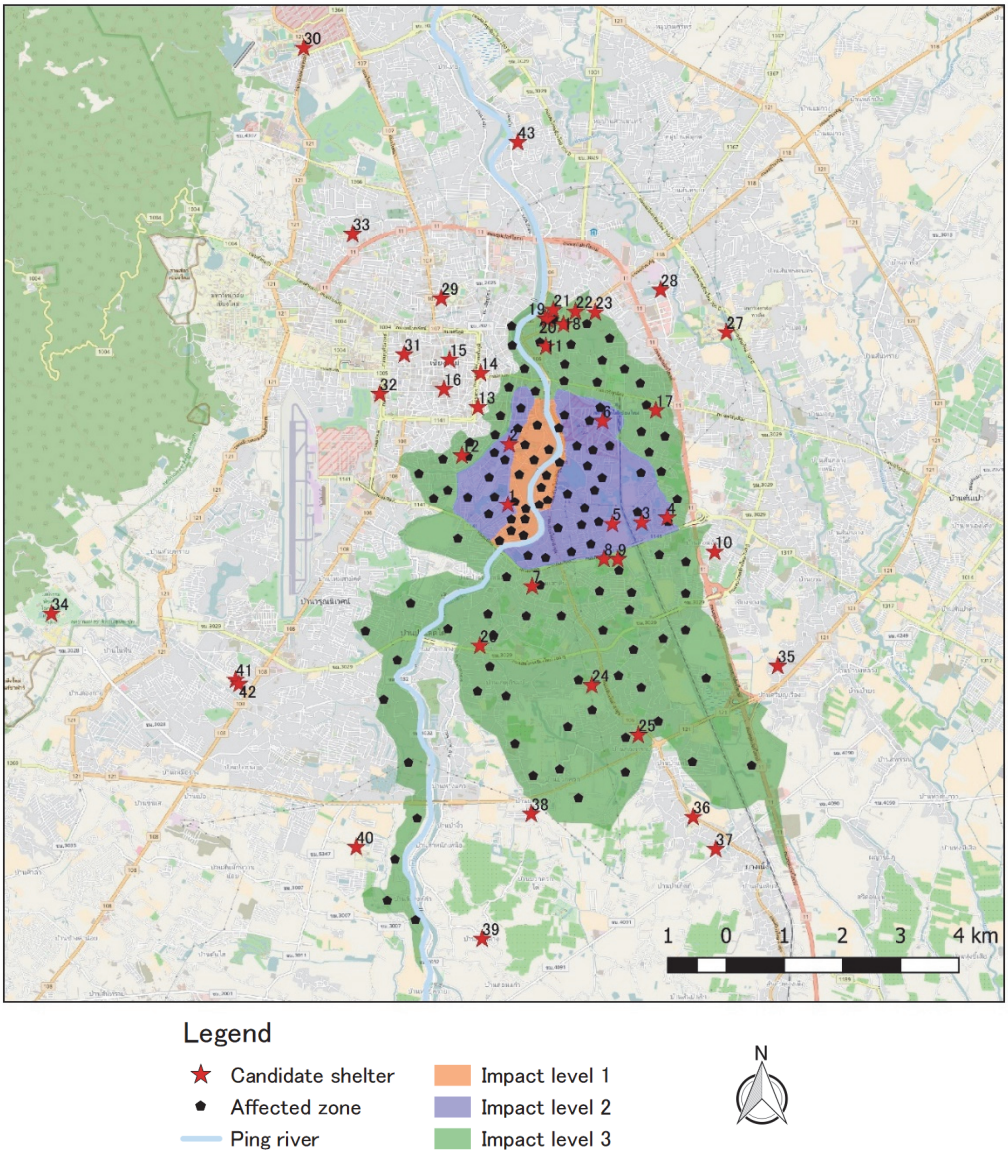


Fig. 7 Geographical location of three impact level areas, candidate shelters, and affected communities in Chiang Mai, Thailand.

meters[27]. Not that the remaining percentage is the people who do not need to evacuate. Finally, the maximum limit of selected shelter is assumed as 25 shelters and the utilization of shelter must greater than or equal to 80%.

5. COMPUTATIONAL RESULT

We solved the proposed mathematical model using the Gurobi Optimizer Ver. 6.0.0 mathematical programming solution software. All experiments were run on a personal computer with an Intel (R) Core (TM) i7-6700 CPU (3.40GHz) and 16 GB of RAM.

(1) Result

After we code and solve the mathematical model into optimization solver software. **Fig. 8** shows the scheme of evacuation planning and flood shelter site location. According to the formulated system, the total expected population-weighted travel distance is 5,729,246. Among the 43 candidate shelters, 24 were identified as shelters that operate at their capacity to serve the communities during flood disaster occurrence. In the first evacuation period needs at least 4 shelters for supporting evacuees in which shelter 1, 2, 7 and 11 are selected, while the total expected population-weighted travel distance in this evacuation period is 1,695,470. The selected shelter of the second evacuation period consists of shelter 7-9, 11-14, and 17. The total expected population-weighted travel distance of the second evacuation period is 2,810,010. For selected shelter of the third evacuation period, there are shelter 10, 13-16, 27-29, 31-32, 35-38, 40 and 42, while the total expected population-weighted travel distance is 1,223,770.

Following the conceptual model, the solution of this formulated system is able to describe that if the flood warning system alarms for the 1st evacuation, the square symbol is opened for supporting evacuees in the 1st impact level zone (Orange zone), in which there are shelter 1, 2, 7 and 11. In the case of expansion of flood zones to the second zone, the 2nd evacuation period will be started. The triangle symbol is opened for supposing evacuees in both the 1st impact level (Orange zone) and the 2nd impact level (Violet zone) that consists of the shelter 8-9, 12-14, and 17. While the selected shelters in the 1st evacuation period where locate out of impact zone are still used for supporting evacuees, there are shelter 7 and 11. Finally, in the case of huge flooding, the shelter 10, 15-16, 27-29, 31-32, 35-38, 40 and 42 are opened (Pen-

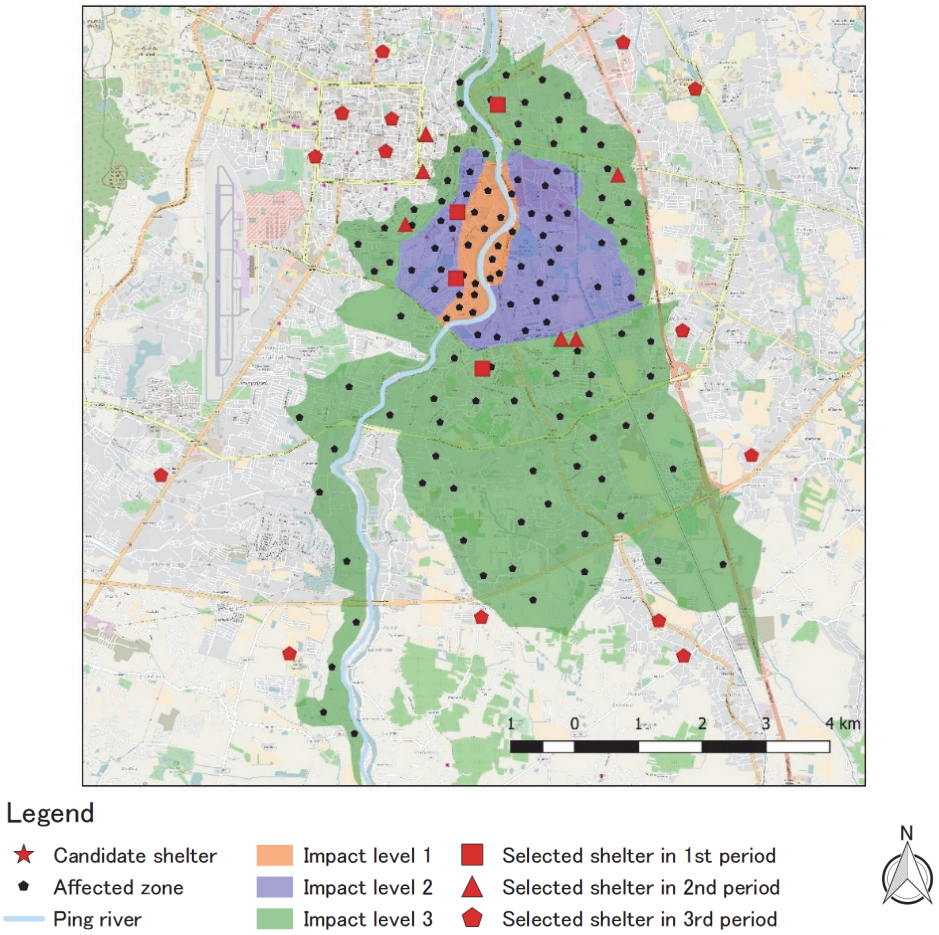
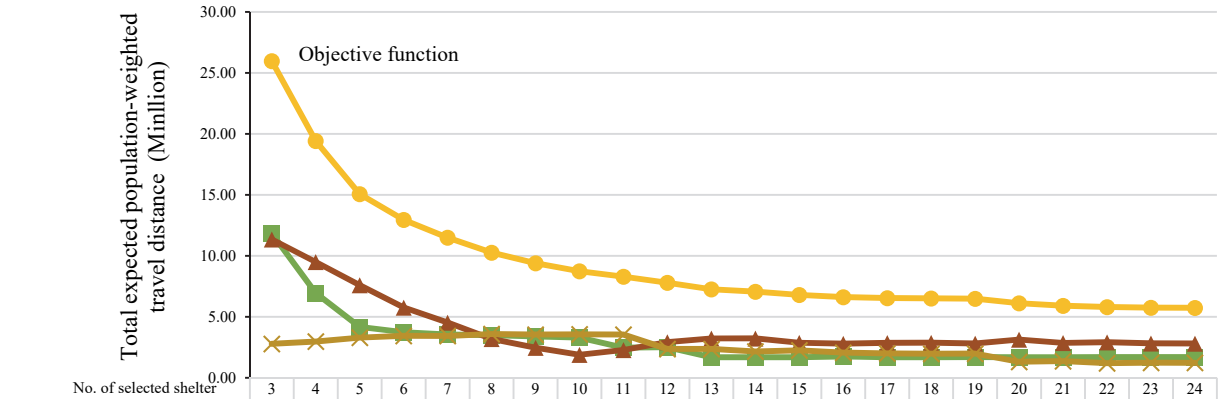


Fig. 8 The scheme of flood-shelter location and evacuation planning under hierarchical evacuation concept.



No. of selected shelter	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
The objective function	25.96	19.42	15.07	12.94	11.50	10.26	9.39	8.74	8.29	7.80	7.26	7.06	6.79	6.61	6.54	6.51	6.48	6.12	5.90	5.80	5.74	5.73
The 1st evacuation period	11.83	6.95	4.18	3.75	3.54	3.49	3.39	3.29	2.46	2.51	1.67	1.67	1.67	1.75	1.67	1.67	1.70	1.67	1.67	1.70	1.70	1.70
The 2nd evacuation period	11.36	9.50	7.59	5.76	4.53	3.18	2.47	1.89	2.29	2.92	3.23	3.23	2.87	2.80	2.87	2.87	2.81	3.13	2.87	2.91	2.82	2.81
The 3rd evacuation period	2.78	2.97	3.29	3.44	3.43	3.59	3.54	3.56	3.54	2.36	2.36	2.16	2.25	2.06	2.00	1.96	1.98	1.31	1.36	1.19	1.23	1.22

Fig. 9 The derived total expected population-weighted travel distance under the different total number of selected shelter.

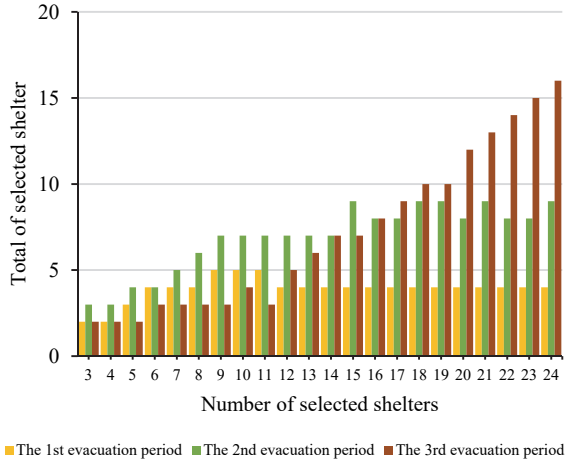


Fig. 10 The derived total number of selected shelter in each evacuation period under the different total number of selected shelter.

tagon symbol) and the shelter 13 and 14 (Triangle symbol) are still opened for supporting evacuees of three hazard areas. The decision makers can plan to follow hierarchical evacuation model. However, some evacuation periods can be skipped over, in which it depends on the decision of decision makers and situation. Note that the selected shelters in previous evacuation period where to locate in next impact level zone are closed. The evacuees in those shelters are evacuated to new shelters. For example, in 2nd evacuation period, the selected shelters (Triangle symbol) in 1st evacuation period that locate in impact level 2 will be closed (Shelter No. 1 and 2).

(2) Sensitivity analysis

In this section, we present a sensitivity analysis to show how the parameters affect the results with respect to changing input parameters. The total number of selected shelter constraint is a major constraint that impinging on both shelter site selection and evacuation planning. The total number of shelter constraint was varied from 24 shelters to 3 shelters, in decrements of 1, to represent the different total number of the shelter with aspect to an objective function as shown in **Fig. 9**. Moreover, we also represent the derived total number of selected shelter in each evacuation period under the different total number of selected shelter as shown in **Fig. 10**. Both of the figures show the result when the model is run multiple time with varying the total number of selected shelter. The graph presents not only the total expect population-weighted travel distance but also and the total expect population-weighted travel distance in each evacuation period. The result found that when the total number of selected shelter is decreased, the total expected population-weighted travel distance is continually increased. At first glance, the gradual increase in the maximum number of selected shelter appears to reduce the total expected population-weighted travel distance. However, when we provide less number of selected shelter, it will threat to the total expected population-weighted travel distance, it may make likely that evacuee will be forced to endure a longer transfer distance. Especially, when we set the number of selected shelter less than 10, the total expected population-weighted travel distance is rapidly increased. According to this sample data set, the formulated system is unable to aid all affected communities if the number of selected shelter is less than 3. The objective function, on the other hand, is unchanged when the maximum total number of selected shelter has more than 24 shelters according to the same performance of each response result. According to the bound of the number of selected shelter is decreased with its decrements, some shelters are removed from

the previous list in which shelter selection depends on its significance.

According to the first evacuation period is significant to objective function because the probability of flooding this period is the highest, so the system attempts to make the shortest distance in this period that affects to shelter site selection. In the first evacuation period, the expected population-weighted travel distance is constant over time during the total number of selected shelter as 22-24. After that, it is slightly increased. The trend of this evacuation period exhibits similar trends as the objective function. The total number of selected shelter in this evacuation period is selected between 2-5 shelters. In the second evacuation period, the expected population-weighted travel distance is higher than the first evacuation period although the probability of this evacuation period is less than the first evacuation period because the shelters are located farther from affect zone and the number of community is also increased. However, when the total number of selected shelter is set at 6-9 shelters, the expected population-weighted travel distance is less than the first evacuation period. The maximum of the number of shelters in this period requires 9 shelters for minimum the expected population-weighted travel distance, while this evacuation period needs at least 3 shelters for covering all demands. For the third evacuation period, the trend is gradually changed because this evacuation period has the least probability of flood occurrence. The expected population-weighted travel distance in this period is slightly increased when the number of selected shelter is decreased. The number of selected shelter in this evacuation period need at least 16 shelters when the selected shelter limit is provided at 24 shelters. On the other hand, the number of selected shelter in this evacuation period need at least 2 shelters when the selected shelter limit is provided at the minimum total number of selected shelter.

Controls the utilization of selected shelter areas is one constraint that can impact the formulated system. We presented the derived total expected population-weighted travel distance and the derived total number of selected shelter under the different value for utilization of selected shelter areas, as shown in **Fig. 11** and **12**. Moreover, **Fig. 11** and **12** also present the result of the unlimited number of shelter site selection. The value for utilization of selected shelter areas was varied from 0 to 1, in increments of 0.1. From **Fig. 11** and **12**, we see that the best objective value of both solutions is reached at the minimum value for utilization of selected shelter areas. If we increase this value with its increments, the objective function (Z1) is exponentially increased. The objective value of the limited number of shelter site selection is higher than the objective value of the unlimited number of shelter site selection during the value for utilization of selected shelter is set at 0-0.5. However, during 0.6-0.9, the objective value has the same result, including the number of selected shelter. In the limited number of shelter site selection, the total expected population-weighted travel distance is stable as approximately 5.544 million during the value for utilization of selected shelter areas is set at 0-0.4. Then, the trend of the objective function is increased step by step. On the other hand, the total number of selected shelter is decreased when the value for utilization of selected shelter areas is increased. During the value for utilization of selected shelter is set at 0-0.5, the total number of selected shelter is stable about 25 shelters. Then, it drops to 24 and 23, respectively. For the unlimited number of shelter site selection, the total expected population-weighted travel distance is started with 5.527 million, while this formulated system needs to open 29 shelters. The objective value is then continually increased while the total number of selected shelter is simultaneously decreased. The both formulated system end at 0.9 for the relief response to

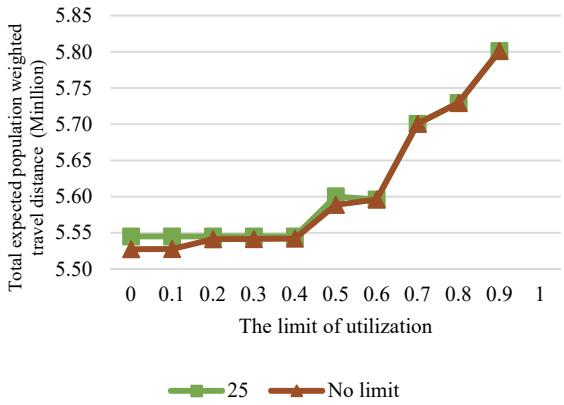


Fig. 11 The derived total expected population-weighted travel distance under the different utilization of selected shelter areas.

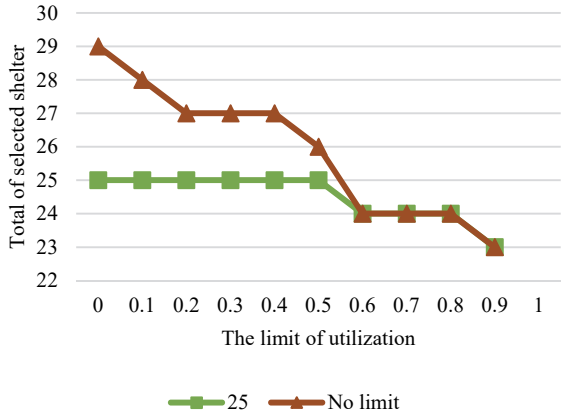


Fig. 12 The derived total number of selected shelter under the different utilization of selected shelter areas.

be feasible. From the result of **Fig. 11** and **12**, it implies that the value for utilization of selected shelter is impinging on the travel distance of evacuee. If the government or policy makers provide too much the value for utilization of selected shelter, it may make likely that evacuee will be forced to endure a longer transfer distance. On the other hand, if the government or policy makers provide too few the value for utilization of selected shelter, it may make likely that the government has to open more shelter in which the government has to support more finance for establishing shelters.

Furthermore, we present the fluctuation of the expected population-weighted travel distance under the different situation of the probability of flooding. This is one of the criteria that can threaten to the objective function. We conducted computational experiments to illustrate how the case study varies when the situation of the probability of flooding is changed. We proposed three scenarios for testing case study in which the probability in each experiment is shown in **Table 3**. In the scenario 1, the probability of the impact level 1 is the highest chance of flooding while the impact level 2 and 3 are low chance of flooding. In the scenario 2, the probability of the impact level 1 and 2 is the biggest proportion to occur flooding except for the impact level 3. Finally, in the scenario 3, all impact levels are the same proportion of flooding chance. Moreover, the probability value of each impact level of a case study that proposed in section **5(1)** is also represented in the last row of **Table 3**.

Three computational experiments are run and showed the result in **Fig 13**. The three schemes of flood evacuation planning and shelter site selection under the different scenarios are shown in **Fig. 14**. We can see that the scenario 1 is quite same the case study in which the shelters located in impact level 2, 3 and non-impact area and the evacuation planning is generated under hierarchical evacuation concept. The objective function is 3.669 million while the total number of selected shelter is 23 shelters. The three shelters (Square symbol) are opened for the first evacuation period. Then, the eight shelters (Triangle symbol) are opened for the second evacuation period in case of extension of flood zone to the second zone (Violet zone). While the shelters that locate out of impact level 2 is still used for supporting evacuees.

Table 3 The computational experiments of the probability of flood occurrence.

Scenario	Impact level 1	Impact level 2	Impact level 3
1	0.90	0.09	0.01
2	0.49	0.49	0.02
3	0.33	0.33	0.33
Case study	0.73	0.25	0.02

Finally, if the expensive flood will occur, twelve shelters (Pentagon symbol) is opened for supporting evacuees of three hazard zones including to two shelters (Triangle symbol) that locate out of impact level 3 zone (Green zone). In the scenario 2, the selected shelters are only located in impact level 3 and the non-impact area. The objective is 7.125 million while the total number of selected shelter is 22 shelters. In this case, the six shelters (Square symbol) are proposed to open for the first evacuation period. Then, the two shelters (Triangle symbol) are selected to open for the second evacuation period, while the selected shelters in the first evacuation period are still used for supporting the second evacuation period as well. Finally, in the case of biggest flooding, the fourteen shelters (Pentagon symbol) are selected including to the selected shelters in previous evacuation periods that locate out of the affected zone. For the scenario 3, all selected shelters are established in the non-impact area. In this case, it seems that this plan is no hierarchical evacuation planning. However, the evacuation planning will evacuate three times that starts with impact level zone 1, 2, 3, respectively. The square symbol is firstly opened, then following with triangle symbol and pentagon symbol, respectively. The objective value in this plan is the highest to estimate to be 22.601 million, while the total number of selected shelter is 16 shelters.

According to the result of the derived expected population-weighted travel distance under the different situation of probability of flooding, we found that if the impact level 1 is a large proportion for probability of flooding, the first evacuation period is the most important in which the nearby shelters are selected because the objective function aims to make the minimum expected population-weighted travel distance in this evacuation period. On the other hand, when all impact level has same proportion for the probability of flooding, the objective function aims to make the short distance in all evacuation period.

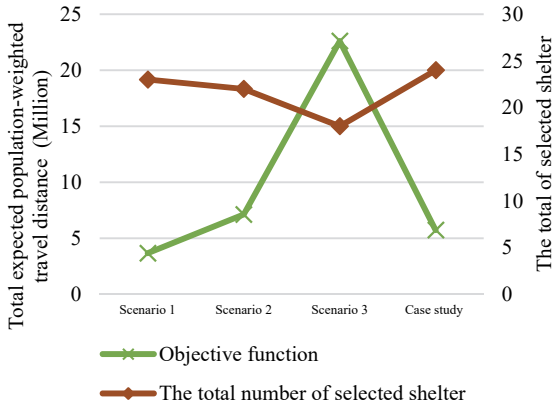


Fig. 13 The derived objective function and total number of selected shelter under the different scenarios.

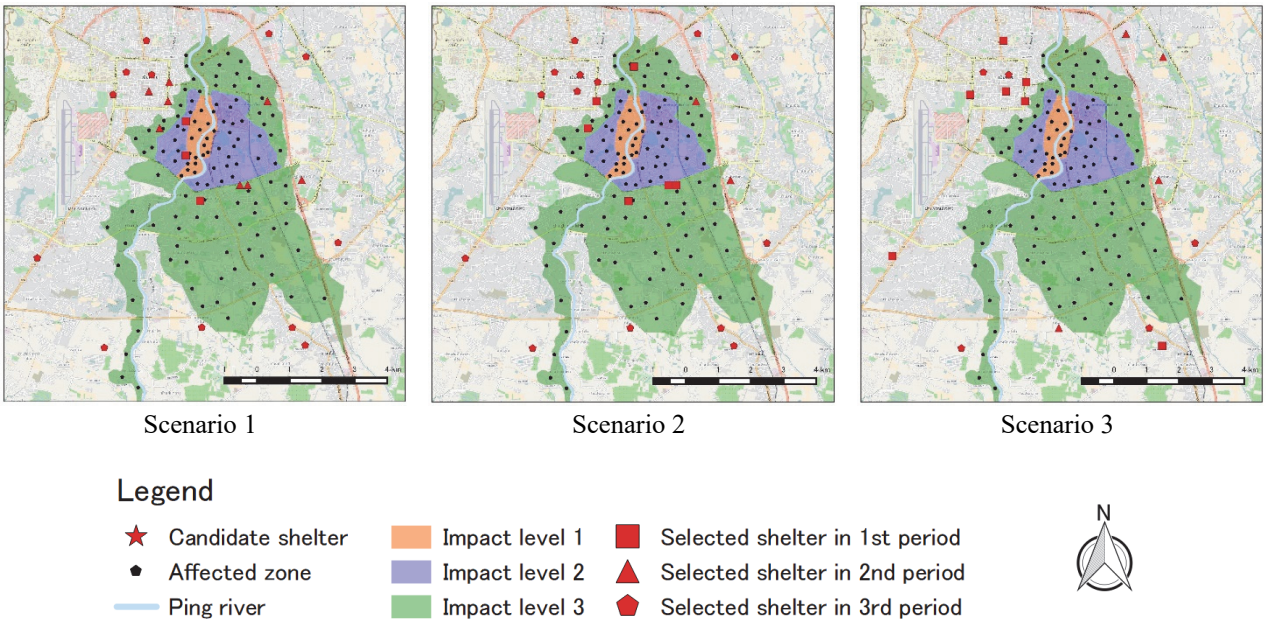


Fig. 14 The three schemes of flood evacuation planning and shelter site selection under the different scenarios.

To recommend for decision making's government in the future, if they use the expected probability based on historical data by CENDRU, they should select the proposed evacuation planning for this case study that shows in **Fig. 8**. If government expect that the severity of flood disasters will be reduced in the future by improving or controlling the Ping river, they can use the scenario 1. On the other hand, if government expect that the severity of flood disasters will increase in the future, they should select the scenario 2 or 3 for flood evacuation planning and shelter site selection. However, the government or policy-makers should be interested in the number of open shelters and the utilization of shelter because it represents the efficient flood evacuation planning including financial and evacuation distance[23]. Finally, the final point depends on policy maker's preference.

(3) Advantage of proposed conceptual model

Our conceptual model can serve emergency management purposes. The first is to help in preparation stage including spatial distribution of shelter under uncertainty of flood occurrences. The second is to aid in response stage in order to provide evacuation flow and directions at each evacuation period. The third is to help in recovery stage for reentry process in term of distance[26]. Our conceptual model also considers utilization of shelter, capacity restriction of shelter and evacuee's behavior that reflect the real problem constraints. Furthermore, when the flood disaster occurs with low-impact events, the evacuees do not need to evacuate to the shelter with a longer transfer distance and the local government can reduce the budget as well. Although this evacuation planning is designed based on hierarchical evacuation planning, it is not necessary to evacuate following the step of the plan. If the local government can predict that the severity of flooding will occur with the expensive flood, the local government can skip over the first or the second evacuation period to the next evacuation period in which this depends on the decision making's local government.

(4) Current problem – to – solution findings

As stated earlier, this case study is faced with flood disaster almost every year. However, in the reality of this problem, many times there are errors and inefficient performance issues including unsuitable opened shelter site, inadequate capacity of shelter, long distance evacuation in perspective of evacuee and amiss assignment.

In this study, we determined that our proposed conceptual model could overcome those happenable problems. Moreover, this could consider the behavior of evacuees during the evacuation, utilization of selected shelter area, and the uncertain situation of flooding, simultaneously. To compare the performance with previous evacuation plan of the case study, in which the local government always select shelter No. 30 and No. 34 for supporting evacuees whenever flooding, our model can reduce the expected population-weighted travel distance to estimate be 80% with respect to the formulated system and can cover all of the demand points in each affected zone. Note that the binary of the other shelters is set as 0 except shelter No. 30 and 34 in the system. Although this can reduce the travel distance of evacuation, this is faced with risk problem of open shelter at potential flooding area, the assignment of this rather complicates due to the behavior of evacu-

ees and some communities might have to evacuate several times. However, this proposed system can apply with the real-world case and respond to evacuee's behavior and uncertain situation of flooding as well.

To improve preparedness, the government should provide more efficient forecast. This proposed model should consider in road closures or traffic congestion, a difference of travel speed depending on the mode selection, accessibility of shelter site, financial cost[28] and risk of open shelter at potential flooding area. Besides, this should consider how to classify evacuation period in which it could affect to the effectiveness of evacuation as well.

6. CONCLUSIONS

This study presented a stochastic linear mixed-integer programming mathematical model for flood evacuation planning to optimize decision related to shelter site selection under hierarchical evacuation planning. The proposed mathematical model considers minimum expected population-weighted travel distance as the objective function. This study not only provides a flood shelter but also determines hierarchical evacuation concept, distribution of shelter, utilization of shelter, capacity restrictions of shelter and evacuee's behavior for flood disaster that balances the preparedness and risk despite the uncertainties of flood events. Our proposed model was validated by generating a base case scenario using real data for Chiang Mai province, Thailand. Besides, we also proposed sensitivity analysis for more guideline under uncertainty decision. This study will be great significance in helping policymakers consider both spatial and performant aspect of the strategic placement of flood shelters and evacuation planning under uncertainties of flood scenario.

The implementation of the proposed mathematical model also has limitations. According to unlike another natural disaster, it cannot be generated to others disaster due to some condition of each natural disaster are different such as shelter type, time condition, etc. However, our mathematical model can apply to any other city in flood situation as well. Although this proposed conceptual model is quite complicated, it can respond to many criteria completely. Consequently, the policymaker should decide carefully to apply with a real case. To reduce a complexity, the affected communities should not be separated too many because it will be difficult for evacuation management. In future research, the proposed model should consider in road closures or traffic congestion, road network, a difference of travel speed depending on the mode selection and accessibility of shelter site that may affect to an efficient evacuation. Furthermore, this model should consider financial cost and risk of open shelter at potential flooding area as well.

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