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Typhoon track change–based emergency shelter location–allocation model: a case study of Wenchang in Hainan province, China

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ABSTRACT

Background Determining the locations of disaster emergency shelters and the allocation of impacted residents are key components in shelter planning and emergency management. Various models have been developed to solve this location–allocation problem, but gaps remain regarding the processes of hazards. This study attempts to develop a model based on the change of typhoon track that addresses the location–allocation problem for typhoon emergency shelters.

Purpose To consider the changes in candidate shelters and number of evacuees due to the change in impact area with the progression of a typhoon.

Methods The proposed model is composed of several static processes and solved by a modified particle swarm optimisation algorithm with a restart strategy.

Results The model is illustrated with the case of the evacuation process for Wenchang in Hainan province during Typhoon Rammasun in 2014 and Typhoon Mirinae in 2016. For the case of Typhoon Rammasun in 2014, the residents from east to west need to evacuate in three phases. For the case of Typhoon Mirinae in 2016, residents in the northern communities need not to evacuate to candidate shelters because they are not affected by the typhoon.

Conclusion The proposed model has advantages compared with non-typhoon track change–based model in saving time spent in shelters for residents and saving public resources for the local governments. With the proposed model, a manager could efficiently evacuate residents by considering the typhoon conditions.

in disaster shelter planning to solve complex and high-dimensional location and allocation problems, such as works performed by Sherali *et al.*,⁹ Dalal *et al.*,¹⁰ Bayram *et al.*,¹¹ Gama *et al.*¹² and Kilci *et al.*¹³ Optimum algorithms, such as the ant colony algorithm,¹⁴ genetic algorithm^{15 16} and particle swarm optimisation (PSO) algorithm,^{5 17–20} have also been adopted to solve the problems of disaster emergency shelter location and allocation. However, in emergency shelter location and allocation model, few studies have considered the process of hazards, which mainly determine the impact areas and number of evacuees.

This study aims to develop a typhoon track change–based shelter location and allocation model using the case of Wenchang in Hainan province, China. In this model, evacuees and candidate shelters are calculated with forecasted change of typhoon tracks. The proposed location and allocation model is then solved by a modified PSO algorithm with a restart strategy and demonstrated in Wenchang. The results show that the proposed method is effective for typhoon shelter planning and the allocation of evacuees.

The remainder of this study is structured as follows: Section 2 gives a description of the study area and data, Section 3 describes the models and algorithms for the location and allocation of typhoon shelters, Section 4 introduces the experimental results, and Section 5 exhibits the conclusion and discussion.

STUDY AREA AND DATA

Wenchang, which is located in northeastern Hainan province, China, is severely affected by tropical cyclones. According to the Wenzhou Typhoon Network (<http://www.wztf121.com/>), there were 42 typhoons in total that affected Wenchang from 2004 to 2018 (figure 1). For example, Typhoon Rammasun (2014), which made landfall near Wenchang on 17 July 2014, was one of the most destructive typhoons to Wenchang. It caused 12 deaths, 410 injuries, 244 000 evacuees and a direct economic loss of 5.968 billion RMB. Typhoon Mirinae (2016), which partly affected Wenchang, made landfall near Wenchang on 26 July 2016. Typhoon Rammasun (2014) and Typhoon Mirinae (2016) are selected as the cases in this study.

Wenchang has a land area of 2488 km², accounting for 7% of the total Hainan province. The topography of Wenchang is relatively subtle, and the slopes are basically below 10 degrees. By

INTRODUCTION

It has been demonstrated that tropical cyclone intensity increased with global warming.^{1 2} Typhoons striking China, Korea and Japan are predicted to further intensify, which represents an increased threat to people and property in the region³; therefore, future planning for disaster prevention is necessary.¹

More and more attention has been paid to the impacts of natural disasters on our society. Numerous efforts have been made to reduce these impacts. The establishment of emergency shelters has been proven to be one of the most effective ways to reduce the casualties of natural disasters.^{4 5} For a long time, many countries, such as the USA and Japan, have set up disaster shelters and issue-related guidelines.^{6–8} With the development of computer and mathematics technology, mathematical planning methods have been widely used

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Figure 1 Study area and typhoon tracks. (A) The geographical location of Wenchang and the tracks of typhoons that affected Wenchang from 2004 to 2018, (B) the track and impact area of typhoon Rammasun in 2014.

the end of 2016, Wenchang had 17 towns, with a total population of 558 800, including 243 villages, with a population of 353 100; 47 designated typhoon emergency shelters, with a capacity of accommodating 22 859 people; and 53 other shelters (including schools and community/village centres), with a capacity of 204 410 people.

Wenchang has a national highway that connects the northern and southern regions of the city, with a total length of 6432 m. There are 4 provincial highways and 43 county and township roads, with total lengths of 211.0 km and 454.0 km, respectively. There are also 64 roads, with a total length of 71.5 km, and 97 trails, with a length of 425.1 km. The provincial, county and township roads and streets are used as candidate evacuation routes in this study. The shortest distances between each community and each shelter are calculated with the Dijkstra algorithm.

In this study, only the typhoon wind is considered. It is assumed that buildings in urban areas are strong enough for typhoon winds; thus, only 243 villages are considered as the demand points, and approximately 10% of the total population needs to evacuate based on the work of Ma *et al.*²¹

METHODS

Model and setting

In this study, a typhoon track change-based shelter location and allocation model (TTC-SLAM) is first developed and then solved by modification of the PSO algorithm. It is assumed that the residents in buildings that have poor anti-wind capacity within 33 kt (Beaufort scale force 7) are assumed to evacuate, and the roads in the area are not recommended as evacuation routes. The region is sequentially affected by a wind force scale of 7 as a typhoon moves ahead. It is also assumed that residents will not evacuate very early but just before the typhoon comes to make the evacuation more efficient. Figure 2 shows the assumption of the evacuation procedure.

In the first phase t_0 (figure 2A), the current wind force covers two shelters (red hexagons) and three communities (green circles). Due to security issues, these two shelters cannot be used as candidate shelters in this phase, and the residents in these two shelters need to evacuate in the previous phase. According to the forecast, the residents in nine communities (yellow circles) will

Figure 2 Status of shelters and communities during the evacuation process. (A) The first phase t_0 and (B) the second phase t_1 .

Figure 3 Flow diagram of the proposed TTC-SLAM. PSO, particle swarm optimisation.

be affected during the next phase (t_1); thus, the residents in these nine communities need to finish evacuating before the typhoon arrives. For these communities, all shelters that are outside of the area of the current wind force (white regular hexagons) can be used as candidate shelters.

The proposed TTC-SLAM is based on a static model for each phase, and the detailed process is shown in figure 3.

In the first step, a static model for each stage is first developed and then solved by the modified PSO algorithm (left part of figure 3). First, the candidate shelters are sorted by their capacities to find a feasible result ($result_1$) for the candidate shelter to satisfy the capacity constraints (ie, to ensure that evacuees in each community can evacuate safely to shelters). Then, the optimal solution is obtained by the modified PSO algorithm. After that, for each community, the candidate shelters are sorted by their distances to the community. The feasible result ($result_1$) is set as the initial value for identifying a better result with a lower total evacuation distance by the modified PSO algorithm. Thus, the optimal result of the static process can be obtained, which is used as the base of the TTC-SLAM. The details of the static model and the algorithm of the modified PSO are presented in Section 3.2 and Section 3.3, respectively.

In the second step, the TTC-SLAM is developed by combining the static evacuation result and the process of a typhoon. In an evacuation process, in addition to the basic evacuation results of the static processes, the locations of the typhoon centre and wind force radius for both the current and forecasted phases are the initial inputs. The roads within the area of the current wind

force are assumed to be forbidden for travel (ie, all residents in the communities within the current area of the wind force should evacuate to the candidate shelters during the previous phase, and all shelters inside the area of the wind force should not be used as candidate shelters). All communities within the area of the next-phase wind force should evacuate to candidate shelters, and communities that are not covered by the next-phase wind force should also evacuate to candidate shelters if these candidate shelters are in the area of the next-phase wind force. If all residents in the communities evacuate to candidate shelters, or the typhoon leaves the study area, the processes of the location and allocation end. Detailed processes of the proposed TTC-SLAM are shown in figure 3.

Static model formulation

It is assumed that all residents in a community are concentrated at its centre and assigned to one candidate shelter, and would evacuate by car at the same speed. Therefore, the evacuation time only depends on the evacuation distance. Thus, a location model with a single objective to minimise the total weighted evacuation distance was proposed. The model has the constraints of service distance and shelter capacity.

$$f = \min \sum d_{ij} B_{ij}, \quad \forall i = 1, 2, \dots, N; \quad \forall j = 1, 2, \dots, M \quad (1)$$

Subject to

$$\sum_{j=1}^M P_j B_{ij} L - S_i Y_i \leq 0, \quad \forall i = 1, 2, \dots, N \quad (2)$$

$$d_{ij}B_{ij} \leq D_j, \quad \forall i = 1, 2, \dots, N; \quad \forall j = 1, 2, \dots, M \quad (3)$$

$$\sum_{i=1}^N B_{ij}Y_i = 1, \quad \forall j = 1, 2, \dots, M \quad (4)$$

$$Y_i = \begin{cases} 1, & i \text{ is selected} \\ 0, & i \text{ is not selected} \end{cases} \quad (5)$$

$$B_{ij} = \begin{cases} 1, & j \text{ selects } i \text{ as an emergency shelter} \\ 0, & j \text{ does not select } i \text{ as an emergency shelter} \end{cases} \quad (6)$$

The sets, variables and parameter definitions in this model are as follows:

I : the set of candidate shelters: $I = (1, 2, \dots, i, \dots, N)$;

J : the set of communities: $J = (1, 2, \dots, j, \dots, M)$;

d_{ij} : the length of the shortest path between community j and shelter i ;

D_j : the maximal evacuation distance for evacuees in community j ;

L : the smallest refuge area per capita ($1 \text{ m}^2/\text{person}$);

P_j : represents the number of evacuees in community j ;

S_i : the remaining area of candidate shelter i .

Equation (1) is the objective function f to minimise the total weighted evacuation distance. The total evacuation distance is minimised subject to the capacity constraint expressed in equation (2) and the distance constraint expressed in equation (3). The capacity constraints require that the areas of the shelters should satisfy the demands of evacuees. The distance constraint requires that the distance from community j to a potential shelter i should not be farther than a specified maximal distance. Equation (4) ensures that each community can only select one shelter. Equation (5) and equation (6) represent Y_i and B_{ij} , which can only be equal to 0 or 1, respectively.

Base of the modified PSO algorithm with a restart strategy

The PSO algorithm²² becomes an important tool to solve complex optimisation problems due to its advantages of fast convergence, robustness and effectiveness. The position update is a major part of the PSO algorithm for improving the efficiency of solving complex problems. An inertia weight is used in the PSO algorithm to balance both the global search and locate search.²³

Although the constriction factor PSO can control the particle's velocity efficiently and enhance the ability of local searching, it is easy to trap into the local optimum.⁵ A restart strategy²⁴ can find a better solution when trapped in the local optimum. A method combining the PSO and restart strategy is proposed to solve the shelter location and allocation problem in this study. The pseudocode of the modified PSO algorithm with a restart strategy is presented in table 1.

RESULTS

Analysis of the results

For the case of Typhoon Rammasun (2014), the schemes of the typhoon location and allocation model for different phases are shown in figure 4. The communities and their assigned shelters are connected with red lines. The blue and cyan areas represent the current and forecasted potential impact areas for 33 kt force winds (force 7 winds), respectively. According to the wind speed, the evacuation process includes three phases. In each phase, communities in the cyan area need to evacuate to shelters to ensure that they are not affected by the typhoon wind. In

Table 1 Pseudocode of the modified particle swarm optimisation (PSO) algorithm with a restart strategy

Algorithm 1 Modified PSO with a restart strategy

1:	$P \leftarrow \text{INITIALIZE}(pSize)$	► Initial particles (P)
2:	for each particle in P	
3:	$v \leftarrow \text{INITIALIZE_V}()$	► Initial particle's velocity
4:	$p \leftarrow \text{INITIALIZE_P}()$	► Initial particle's position
5:	$pbest \leftarrow \text{INITIALIZE_PB}()$	► Initial particle's $pbest$ (denotes the individual optimum)
6:	$gbest \leftarrow \text{INITIALIZE_GB}()$	► Initial $gbest$ (denotes the global optimum by a global structure)
7:	$fitness_{gbest} \leftarrow \text{COMPUTE_FITNESS}(gbest)$	► Compute global fitness
8:	$count \leftarrow 0$	► Counter for times of $fitness_{gbest}$ with the same value
9:	$gbest_{temp} \leftarrow gbest$	
10:	$fitness_{temp} \leftarrow fitness_{gbest}$	
11:	for each iteration	
12:	for each particle in P	
13:	$v \leftarrow \text{UPDATE_v}(p, v, pbest, gbest)$	► Update particle's velocity
14:	$p \leftarrow \text{UPDATE_p}(p, v)$	► Update particle's position
15:	$fitness_{current} \leftarrow \text{COMPUTE_FITNESS}(p)$	► Compute current fitness
16:	$fitness_{pbest} \leftarrow \text{COMPUTE_FITNESS}(pbest)$	► Compute particle's best fitness
17:	if $fitness_{current} < fitness_{pbest}$ then	
18:	$pbest \leftarrow p$	
19:	$fitness_{pbest} \leftarrow fitness_{current}$	
20:	if $fitness_{pbest} < fitness_{temp}$ then	
21:	$gbest_{temp} \leftarrow pbest$	
22:	$fitness_{temp} \leftarrow fitness_{pbest}$	
23:	if $fitness_{temp} < fitness_{gbest}$ then	
24:	$gbest \leftarrow gbest_{temp}$	
25:	$fitness_{gbest} \leftarrow fitness_{temp}$	
26:	$count \leftarrow 0$	
27:	else	
28:	$count \leftarrow count + 1$	
29:	if $count > t_1$ then	► Trap into the local optimum
30:	for each particle in P	► Apply restart strategy
31:	$v \leftarrow \text{INITIALIZE_V}()$	► Initial particle's velocity
32:	$p \leftarrow \text{INITIALIZE_P}()$	► Initial particle's position
33:	$pbest \leftarrow \text{INITIALIZE_PB}()$	► Initial particle's $pbest$
34:	$count \leftarrow 0$	

the first phase (t_1) (figure 4A), Wenchang is not affected by the current force 7 winds but will be affected by the force 7 winds in the next phase (t_2) according to the forecast. In the second phase (t_2), the residents for most of the communities (in the cyan area) have to evacuate to shelters because these communities are estimated to be affected by the typhoon in the third phase (t_3).

There are some intersecting lines in figure 4B. One of the major reasons is that the community has to be assigned to a shelter farther away but with increased capacity because the shelter has a nearly limited capacity for accommodating the evacuees of the community. Another reason might be that the evacuation routes do not intersect. The number of selected and unselected communities and shelters for different phases are shown in table 2. Table 3 listed 10 example shelters with their allocated communities, and evacuation distance and evacuation time for each community.

As shown in table 2, there is one community outside the area of the current wind force for t_1 , which means that this community

Figure 4 Spatial allocation results corresponding to the proposed model for typhoon Rammasun (2014). A: t_1 , B: t_2 , C: t_3 .

will be inside the area of the wind force at t_2 , but it is assigned to a shelter that is affected by the typhoon at t_1 . Thus, the residents of this community have to evacuate to a shelter during t_1 . The six communities outside the area of the current wind force during t_2 are similar.

For the case of Typhoon Mirinae (2016), the shelter location and allocation schemes for different phases are shown in figure 5. Same as Typhoon Rammasun (2014), residents in the areas for force 7 winds are assumed to evacuate during the Typhoon Mirinae (2016). In this case, the evacuation process includes four phases. Residents in the northern communities need not to evacuate to candidate shelters because they are not affected by the force 7 typhoon wind. The result is very different from the allocation planning of conventional model, which generally considers that all residents in communities need to evacuate.

Figures 4 and 5 show that many designated shelters are not selected by the communities due to small capacity or long evacuation distance. To explore the utilisation rate of the designated shelters, the evacuation processes for the 42 typhoons (including Rammasun [2014] and Mirinae [2016]) that affect Wenchang from 2004 to 2018 are also modelled with the modified PSO algorithm. The total capacity and average utilisation ratio of the designated shelters are presented in figure 6.

From figure 6, there are only two designated shelters with a capacity larger than 700. Correspondingly, there are 14 shelters with a capacity less than 200. The total capacity of the 47

Table 3 Details of the communities and assigned shelters for typhoon Rammasun (2014)

Shelter ID	Shelter capacity (person)	Community ID	Evacuation distance (m)	Evacuation time (min)	Number of evacuees (person)	Time spent to start from evacuation to stop receiving evacuees (min)
S1	2000	C1	1154.17	1.731	69	10.004
		C2	1895.28	2.843	100	
		C3	2232.51	3.349	182	
		C4	5889.09	8.834	109	
		C5	7823.84	11.736	145	
S2	4000	C6	11 228.70	16.843	80	9.828*
		C7	7462.95	11.194	64	
		C8	6783.71	10.176	64	
		C9	10 610.30	15.915	58	
		C10	4676.34	7.015	82	
		C11	6796.42	10.195	138	
S3	1000	C12	6173.23	9.260	49	0.935†
		C13	6940.96	10.411	105	
		C14	4834.86	7.252	136	
S4	4000	C15	5390.84	8.086	46	3.159
		C16	3429.91	5.145	174	
		C17	5384.50	8.077	185	
S5	8000	C18	5199.89	7.800	166	11.767
		C19	7944.43	11.917	189	
		C20	5170.14	7.755	86	
		C21	3266.56	4.900	49	
		C22	100.00	0.150	183	
		C23	257.76	0.387	82	
S6	500	C24	2352.35	3.528	93	3.142
		C25	3944.52	5.917	83	
S7	518	C26	431.70	0.648	257	5.269
		C27	1389.08	2.084	156	
		C28	2687.36	4.031	250	
S8	518	C29	3116.07	4.674	130	4.288
S9	678	C30	3922.25	5.883	128	
		C31	2102.94	3.154	178	
		C32	4961.43	7.442	133	
		C33	3959.99	5.940	81	
S10	678	C34	100.00	0.150	36	0.263
		C35	275.63	0.413	104	

*For evacuation phase 2.

†For evacuation phase 3.

Table 2 Details of the community and shelter distributions for different evacuation phases during typhoon Rammasun (2014).

			t ₁	t ₂	t ₃	Total
Covered community		Inside the area of the current wind force	20	176	40	236
		Outside the area of the current wind force	1	6	0	7
		Subtotal	21	182	40	243
Candidate shelter	Designated shelter	Covered	4	33	6	43
		Uncovered	2	0	0	2
		Subtotal	6	33	6	45
	Other shelter	Covered	5	31	6	42
		Uncovered	1	1	0	2
		Subtotal	6	32	6	44
	Total		12	65	12	85*

*Several shelters are counted twice; thus, the total number is slightly different from the sum of the total designated shelters and other shelters.

Figure 5 Spatial allocation results corresponding to the proposed model for typhoon Mirinae (2016).

designated shelters is 22 859, which is much less than the total capacity of the other shelters for 204 410 people. There are 20 designated shelters with a utilisation rate of less than 50%, including two shelters that are not selected by the communities.

Results comparison for two models

The result from the proposed TTC-SLAM is also compared with the result from non-typhoon tracked change-based model (NTTC). In the NTTC model, the objective and constraints are the same as the ones for TTC model; the difference is that for the NTTC model, the whole area is affected by the typhoon and all residents will evacuate to shelters at the same time.

The total number of communities that need to evacuate (nc_{sum}), total number of selected shelters (ns_{sum}), total evacuation distance (d_{sum}) and total time spent in shelters (t_{sum}) from the two models are compared in this study.

The results are shown in table 4. In the case of Typhoon Rammasun (2014), the whole study area was affected, thus t_{sum}

for TTC model is much shorter than the one for NTTC model. In the case of Typhoon Mirinae (2016), only the south part of the study area is affected, thus the values of nc_{sum} , ns_{sum} , d_{sum} and t_{sum} of TTC model are all less than that of NTTC model. The proposed TTC model shows an obvious advantage compared with the NTTC model.

CONCLUSION AND DISCUSSION

Conclusion

In this study, a shelter location and allocation model for typhoon disasters is proposed by considering the process of a typhoon with the case of Wenchang in Hainan province. The proposed model is solved by the modified PSO algorithm with a restart strategy. For the case of Typhoon Rammasun in 2014, the evacuation processes can be divided into three phases. In the first phase (t_1), Wenchang is not affected by the current force 7 winds but will be affected by the force 7 winds in the next

Figure 6 Total capacity and average utilisation ratio of the designated shelters.

phase (t_2). In this phase, 21 communities are assigned to nine shelters. In addition, 182 communities are assigned to 64 and 12 shelters during the t_2 and t_3 phases, respectively. For the case of Typhoon Mirinae in 2016, residents in the northern communities need not to evacuate to candidate shelters because they are not affected by the typhoon. The value of t_{sum} for TCC model is much shorter than that of NTTC model for the case of Typhoon Rammasun (2014), and the values of nc_{sum} , ns_{sum} , d_{sum} and t_{sum} of TCC model are all less than that of NTTC model for the case of Typhoon Mirinae (2016). The proposed TTC model result shows an obvious advantage compared with the NTTC model; it can save time spent in shelters for residents and save public resource without arranging unnecessary evacuation for the local government. With the model, a manager could make decisions for regional shelter and evacuation planning by considering typhoon information.

Discussion

In this study, 57 public facilities such as schools and community/village centres are also considered as candidate typhoon shelters because of the limited total capacity of 47 designated shelters. For the case of Typhoon Mirinae (2016), residents in the communities that were not affected in the whole processes of typhoon do not evacuate, which can effectively save the resource due to unnecessary evacuation. In the final result of the Typhoon Rammasun (2014) case, 85 shelters in total are used, of which 43 are designated shelters and 42 are other shelters. Excluding the use of other shelters, the shelters will be overcrowded because the number of evacuees is greater than the capacities of the

43 designated shelters. In this sense, it is suggested to update other shelters to provide middle-term and/or long-term supplies, instead of building new shelters to save resources.

It has to be noted that in this study all residents in a community are assumed to evacuate to one candidate shelter for simplicity. In reality, residents in a larger community may evacuate separately to several shelters. The evacuation time greatly depends on the evacuation speed, evacuation mode and road conditions. For simplicity, residents are assumed to evacuate by car at the same speed, and road congestion is not considered in the evacuation process of this study. The differences among community size, the evacuation mode, evacuation willingness and road conditions will be considered in our future work, with the results being much closer to the real situation.

What is already known on this subject

- ▶ Disaster emergency shelter location-allocation is a key component in shelter planning and emergency management.
- ▶ Various models have been developed to solve location-allocation problems.
- ▶ The hazard process is often not considered in disaster emergency shelter location-allocation models.

What this study adds

- ▶ The proposed model considers the changes of candidate shelters and number of evacuees due to the change of typhoon track.
- ▶ The proposed model is composed of several static processes and solved by the modified PSO algorithm with a restart strategy.
- ▶ Two typhoons were selected to illustrate the evacuation process for Wenchang in Hainan province.

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Table 4 Analysis of the results between the TTC model and NTTC model

Typhoon	Model	nc_{sum}	ns_{sum}	$d_{sum}(m)$	$t_{sum}(h)$
Rammasun (2014)	NTTC model	243	85	1.4871e+09	1 065 150
	Proposed TTC model	243	85	1.4871e+09	696 129
Mirinae (2016)	NTTC model	243	82	1.4878e+09	1 420 200
	Proposed TCC model	170	58	1.0285e+09	788 471

Both the TTC and NTTC models are solved by the modified particle swarm optimisation algorithm. The values of nc_{sum} , ns_{sum} , d_{sum} and t_{sum} of the NTTC model for two cases are different because they are the results of two optimal solutions.

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REFERENCES

- 1 Tsuboki K, Yoshioka MK, Shinoda T, *et al*. Future increase of supertyphoon intensity associated with climate change. *Geophys Res Lett* 2015;42:646–52.
- 2 Walsh KJE, McBride JL, Klotzbach PJ, *et al*. Tropical cyclones and climate change. *Wiley Interdiscip Rev Clim Change* 2016;7:65–89.
- 3 Mei W, Xie S-P. Intensification of landfalling typhoons over the northwest Pacific since the late 1970s. *Nat Geosci* 2016;9:753–7.
- 4 M W N, Park J, Waller ST. A hybrid bilevel model for the optimal shelter assignment in emergency evacuations. *Comput-Aided Civ Inf* 2010;25:547–56.
- 5 Zhao X, Xu W, Ma Y, *et al*. Scenario-based multi-objective optimum allocation model for earthquake emergency shelters using a modified particle swarm optimization algorithm: a case study in Chaoyang District, Beijing, China. *PLoS One* 2015;10:e0144455.
- 6 Federal Emergency Management Agency (FEMA). *Fema 320: taking shelter from the storm—building a safe room inside your house*, 1998.
- 7 Federal Emergency Management Agency (FEMA). *Fema 361: design and construction guidance for community shelters*, 2000.
- 8 Alameda County Operational Area Emergency Management Organization (ACOAMO). *A guide for local jurisdictions in care and shelter planning*, 2003.
- 9 Sherali HD, Carter TB, Hobeika AG. A location–allocation model and algorithm for evacuation planning under hurricane/flood conditions. *Transport Res B-Meth* 1991;25:439–52.
- 10 Dalal J, Mohapatra PKJ, Mitra GC. Locating cyclone shelters: a case. *Disaster Prev Manag* 2007;16:235–44.
- 11 Bayram V, Tansel Barbaros C, Yaman H. Compromising system and user interests in shelter location and evacuation planning. *Transport Res B-Meth* 2015;72:146–63.
- 12 Gama M, Santos BF, Scaparra MP. A multi-period shelter location-allocation model with evacuation orders for flood disasters. *EURO J Comput Optim* 2016;4:299–323.
- 13 Kılıç F, Kara BY, Bozkaya B. Locating temporary shelter areas after an earthquake: a case for Turkey. *Eur J Oper Res* 2015;243:323–32.
- 14 Li X, He J, Liu X. Intelligent GIS for solving high-dimensional site selection problems using ant colony optimization techniques. *Int J Geogr Inf Sci* 2009;23:399–416.
- 15 Huang B, Yao L, Raguraman K. Bi-level GA and GIS for multi-objective TSP route planning. *Transport Plan Techn* 2006;29:105–24.
- 16 Hu F, Yang S, Xu W. A non-dominated sorting genetic algorithm for the location and districting planning of earthquake shelters. *Int J Geogr Inf Sci* 2014;28:1482–501.
- 17 Hu F, Xu W, Li X. A modified particle swarm optimization algorithm for optimal allocation of earthquake emergency shelters. *Int J Geogr Inf Sci* 2012;26:1643–66.
- 18 Ma Y, Xu W, Qin L, *et al*. Hierarchical supplement location–allocation optimization for disaster supply warehouses in the Beijing–Tianjin–Hebei region of China. *Geomat Nat Haz Risk* 2019;10:102–17.
- 19 Xu W, Ma Y, Zhao X, *et al*. A comparison of scenario-based hybrid bilevel and multi-objective location-allocation models for earthquake emergency shelters: a case study in the central area of Beijing, China. *Int J Geogr Inf Sci* 2018;32:236–56.
- 20 Xu W, Zhao X, Ma Y, *et al*. A multi-objective optimization based method for evaluating earthquake shelter location–allocation. *Geomat Nat Haz Risk* 2018;9:662–77.
- 21 Ma Y, Yuan Y, Pan D. Spatial–temporal distribution characteristics of emergency responses for typhoon disaster relief in China. *J Catastrophol* 2012;3:132–6.
- 22 Eberhart RC, Kennedy J. *A new optimizer using particle swarm theory*. Proceedings of the sixth international symposium on micro machine and human science. 1995. Proceedings of the Sixth International Symposium on. IEEE, 1995:39–43.
- 23 Shi Y, Eberhart RC. *A modified particle swarm optimizer*. Evolutionary computational proceedings. IEEE World Congress on Computational Intelligence, The 1998 IEEE International Conference on. IEEE, 1998:69–73.
- 24 Huberman BA, Lukose RM, Hogg T. An economics approach to hard computational problems. *Science* 1997;275:51–4.