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Evacuation Planning with Flood Inundation as Inputs

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ABSTRACT

Recent flooding events happening in our city demonstrate frequency and severity of floods in the UK, highlighting the need to plan and prepare, and efficiently defend. Different from the numerous evacuation model and optimization algorithms, this paper aims to address flood evacuation planning with flood inundation as inputs. A dynamic flooding model and prediction to estimate the development of both surface water and flooding from rivers and watercourses has been fed into evacuation planning at various levels. A three-step approach is proposed. The first step is to identify assembly point designation. The second step is to find the candidate shortest path from each assembly point to all safe areas for all evacuees with consideration of possible inundation. The last step is to determine the optimal safe area for evacuees in the inundation area. The work presented in this paper has emphasized timing issue in evacuation planning. A case study is given to illustrate the use of the approach.

Keywords

Multi-objective optimization, flood evacuation planning, Genetic Algorithm (GA), Dijkstra’s algorithm

INTRODUCTION

Flood is one of the most costly natural disasters in terms of the social, economic and environmental damages caused, especially in urban areas. Recent extreme flood events in the UK (e.g. 2000, 2007 and 2012, 2014) arising either from fluvial or pluvial sources have caused huge disruptions to the normal running of many cities. “Over 5 million people in England and Wales live and work in properties that are at risk of flooding from rivers or the sea”, according to UK Environment Agency. The first Climate Change Risk Assessment in 2012 highlighted the UK’s vulnerability to extreme weather and flooding. In response, the government launched the ‘National Adaptation Program: Making the country resilient to a changing climate’, in July 2013, which aims to effectively prepare businesses and communities for the risks of flooding. In Leicestershire and Rutland, flooding is the highest priority risk, which is associated with many of the rivers and brooks. Our urban areas are likely to be affected by surface water flooding when heavy, intense rainfall hits. Leicester city is currently one of the top 10 flood risks in the country from a combination of both surface water and flooding from rivers and watercourses. This paper is based on an ongoing research project in Leicestershire and reports the latest achievement in emergency flood evacuation planning.

Environment Agency (EA) has the overall responsibility for managing flood risks in the UK. Flood risks mapping by the EA is undertaken by consultancy companies using commercial flood modelling software. This is typically based on scenario-based studies, looking at flood risks with various return periods. Deliverables of such modelling exercises are static maps showing extent of inundation. Local authorities such as Leicester Fire and Rescue Services (LFRS) and Leicestershire County Council (LCC) then use such maps provided by EA for planning and emergency management. There is a clear demand from local decision makers that flooding risk can be predicted and then prevented via evacuation planning. Our project seeks to meet the demand and allow a more flexible approach to flood evacuation planning at the local level.

This paper is structured as follows. The following section reviews most commonly used evacuation planning research. Then generic flood inundation model is presented which will be used as input to the proposed evacuation planning. Afterward the three-step approach is proposed for evacuation planning. A numerical case study is described in which the proposed approach is applied to. Finally concluding remarks on the potential of the proposed method and possible impact on social, environmental and cultural aspects are provided as the end.

EVACUCATION PLANNING RESEARCH

There are different studies in evacuation planning that work from different perspectives such as evacuee behaviours, traffic control strategies, sheltering site selection and determination of the number of sheltering, and route finding for displacement. Generally speaking, evacuation planning is classified into microscopic planning and macroscopic planning (Hamacher and Tjandra, 2002). Microscopic planning assesses evacuee's behavior and movement while macroscopic planning encompasses on the various operations and the population to be evacuated in macroscopic evacuation planning.

Evacuee behaviours can be classified into the microscopic evacuation planning category. For example, Murray and Mahmassani (2003) dealt with household behavior as a single unit. It was assumed that the household members meet each other at a meeting point and is evacuated together. This household behavior was included in the evacuation modelling which forms a linear integer programming problem.

Different models were proposed to maximize the traffic volume entering the controlled area and to minimize the rescue time in disaster area (Feng and Wen, 2003). A location-allocation model was proposed to select a set of candidate shelters from among the potential shelters and to prescribe an evacuation plan which minimize the total evacuation time. The optimal problem is formulated as a nonlinear mixed integer programming problem (Sherali et al, 1991). Kongsomsaksajul et al (2005) proposed a two level optimization problem for flood evacuation planning. The shelter location and the number of shelters are determined at the upper level for the authority. The shelter and route to evacuate is determined at the lower level for the evacuees. The optimization problem is formulated as a Stackelberg game.

Most of the data required for emergency management and evacuation planning have a spatial component or location which geographical information system (GIS) can facilitate (Mansourian et al., 2006; Saadatseresht et al., 2009). Pal et al. (2003) have discussed the development of a traffic simulation methodology using GIS and spatial data, which could be used for emergency evacuation planning purpose. Saadatseresht et al. (2009) addressed the use of multi-objective evolutionary algorithms and the GIS for evacuation planning. It proposed a GIS based three-step approach for evacuation planning. In the first step appropriate safe places for evacuation are selected. In the second step, for each building block, initial candidate safe areas are selected. In the third step, optimum distribution of people to the safe areas is determined through a multi-objective evolutionary optimization approach.

The approach proposed in our work here is similar to Saadatseresht et al.'s three-step approach in terms of the actual steps as they are common sense, but unique in terms of emphasized timing issue in evacuation planning as, for example, some routes were accessible 30 minutes ago but are not now because of the development of both surface water and flooding from rivers and watercourses. The algorithms implemented in each step are also without parallel to any existing evacuation planning approaches. The main contribution to knowledge made in this work is on the formation of the flood evacuation planning as a binary optimization problem. This paper focuses on macroscopic evacuation planning as evacuee's behavior and movement have not been considered here.

FLOOD INUNDATION MODEL

Most emergency evacuation in response to flooding has treated flood risk as a static factor, usually informed by flood risk maps. However, flooding is a dynamic phenomenon and apart from the magnitude of a flood event, emergency evacuation also needs to consider other flood characteristics, e.g. the time of occurrence, duration and rising rate of the flood water. Such flood characteristics can be readily obtained from hydraulic modelling, i.e. flood inundation modelling (Bates and De Roo, 2000). A 2D flood inundation model (FloodMap) developed by Yu and Lane (2006a, b) has been chosen to simulate the flood inundation dynamics and the result will be used as input in the evacuation planning in this paper due to its simplicity and customized parameters for Leicestershire and Rutland in the UK. The 2D flood inundation model (FloodMap) can be used to simulate the flood inundation dynamics with high resolution topographic data in urban areas. The model is in generic and has been customized before applying for Leicestershire and Rutland region.

The model is the basis of the sub-grid treatment approach developed by Yu and Lane (2006b) and its parallel version FloodMap-Parallel (Yu, 2010) and has been tested and verified with a range of boundary conditions and in a number of environments (e.g. Tayefi *et al.*, 2007; Lane *et al.*, 2007; Lane *et al.*, 2008). The coupled model assumes that the floodplain is protected by an embankment that essentially acts as a continuous, broad-crested weir through which flow exchange occurs between the channel and floodplain. A tightly-coupled approach solves the one-dimensional river flow and two-dimensional floodplain flows simultaneously in a raster environment. The one-dimensional in-channel model solves the full Saint-Venant equations for unsteady open-channel flow using the Preissmann scheme based upon the fixed bed model of Abbott and Basco (1989).

Figure 1 illustrates the inundation extent over different time resulted from the 2D flood inundation model. The development of both surface water and flooding from rivers and watercourses is shown, from which the accessibility of any route from an emergency planning zone to a shelter is obtained at any time. The route accessibility is time-various as some routes were accessible 30 minutes ago but may not at this moment.

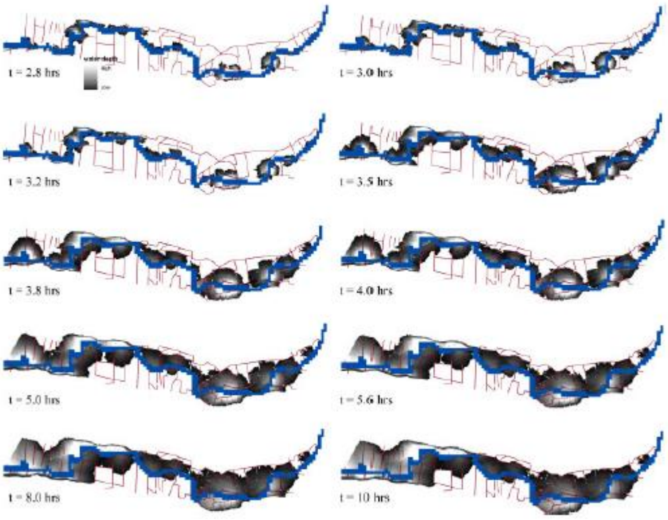

Figure 1. Inundation extent over time

EVACUATION PLANNING WITH INUNDATION AS INPUT

This section gives an overview of the three-step flood evacuation planning approach with inundation as input. The flood inundation model described in the previous section is a continuous temporal model. The inundation extent should be transformed into a discrete domain, say every 30 minutes. The evacuation planning algorithm is conducted in the same time interval. The latest inundation extent is used to determine the accessibility of any route to the safe areas. The emergency planning zone is divided into blocks depending on the living density. The evacuation planning algorithm is proposed to decide where to evacuate people within the capacities of the safe areas and decide on the routes to take with the shortest distance to the safe areas.

In detail, a three-step evacuation planning algorithm is proposed in this paper. As illustrated in Figure 2, the first step is safe area selection which can be preliminarily determined before floods occur. The second step is to find the candidate assembly points or safe areas for all evacuees with consideration of possible inundation. The last step is to determine the optimal evacuation route for evacuees in the emergency evacuation zone. The accessibility of all the routes is updated every 30 minutes after the inundation model is executed. The latest accessibility of the routes is fed into the shortest path searching.

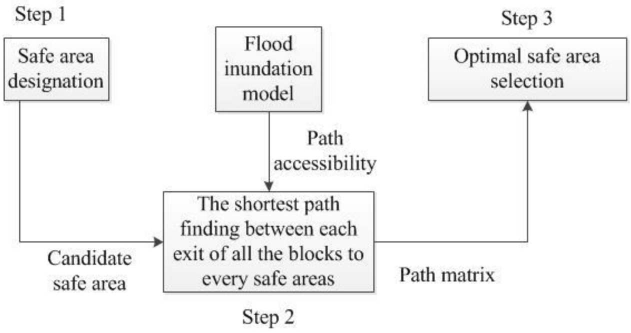

Figure 2. Three-step evacuation planning with inundation model as input

Assembly points designation

The assembly points can be determined in advance before flood events occur. The basic requirements of these areas are enough space for evacuees, basic living supply and safe from inundation threats. The local authorities should collect enough information for making the decision on where these assembly points should be. In this research we simply assume that the number of the assembly points and the location of them have been predetermined by the local authorities. The assembly points are also named as safe areas in this paper which are used interchangeably.

Shortest path finding

The emergency planning zone is divided into different blocks in terms of the living density. All available paths from each exit of every block to every safe area are calculated by the Dijkstra algorithm and presented in a path matrix. Rows in the path matrix represent the exits of all the blocks with evacuees, columns represent the possible safe areas. The elements of the matrix represent the distance from the exit to the safe area. This path matrix is updated every 30 minutes as some paths may become non-accessible after inundation is developed. The output of the execution of the inundation model is represented in a 2D map and indicates the accessibility of each path.

The Dijkstra algorithm (Skiena , 1990) is used to calculate the distance from an exit of blocks to all safe areas in a shortest path. The basic idea is to establish the set of vertices and expand it by greedy algorithm constantly until it is finished so that the shortest path is obtained.

Optimal safe area selection

Notation	Description
B_{ij}	the jth exit of Block i
R_k	the kth safe area
p_{ijk}	the population at the jth exit of Block i are evacuated to the kth safe area in the identified shortest path
C_k	the capacity at the kth safe area
d_{ijk}	the shortest distance from B_{ij} to R_k
U	the first objective function
V	the second objective function

Table 1. Notation

Once the candidate shorter paths are identified for each exit of all blocks, the proper safe area for the evacuation of the evacuees in each exit of any block can be determined by solving a multi-objective optimization problem. We adopt the two objective functions proposed by Saadatseresht et al. (2009) but solve it based on the path matrix obtained in the previous step. For the sake of simplicity we use the notation shown in Table 1 in the multi-objective optimization formula shown in Eq. 1 and 2.

$$\min U = \sum_k \left| \sum_i \sum_j p_{ijk} x_{ijk} - C_k \right| \tag{1}$$

$$\min V = \sum_k \sum_j \sum_i d_{ijk} p_{ijk} x_{ijk} \tag{2}$$

$$x_{ijk} = \begin{cases} 1 & if \quad R_k \quad is \quad assigned \quad to \quad B_{ij} \\ 0 & otherwise \end{cases} \tag{3}$$

The first objective function shown in Eq. 1 means that the total population assigned to each safe area should be near to its capacity. The second objective function shown in Eq. 2 means that the evacuation should be conducted in the shortest possible path, i.e. in the shortest possible time.

As Saadatseresht et al. (2009) presented that there are various ways to solve the two-objective optimization problem. Following the way used in Yang et al. (2007) the above two objective functions can be combined into a single objective function as shown in Eq. 4. The objective problem becomes to find the proper values of the decision variables shown in Eq. 3 to minimize Eq. 4.

$$\min(U+V) = \sum_k \left| \sum_i \sum_j p_{ijk} x_{ijk} - C_k \right| + \sum_k \sum_j \sum_i d_{ijk} p_{ijk} x_{ijk} \tag{4}$$

NUMERICAL CASE STUDY

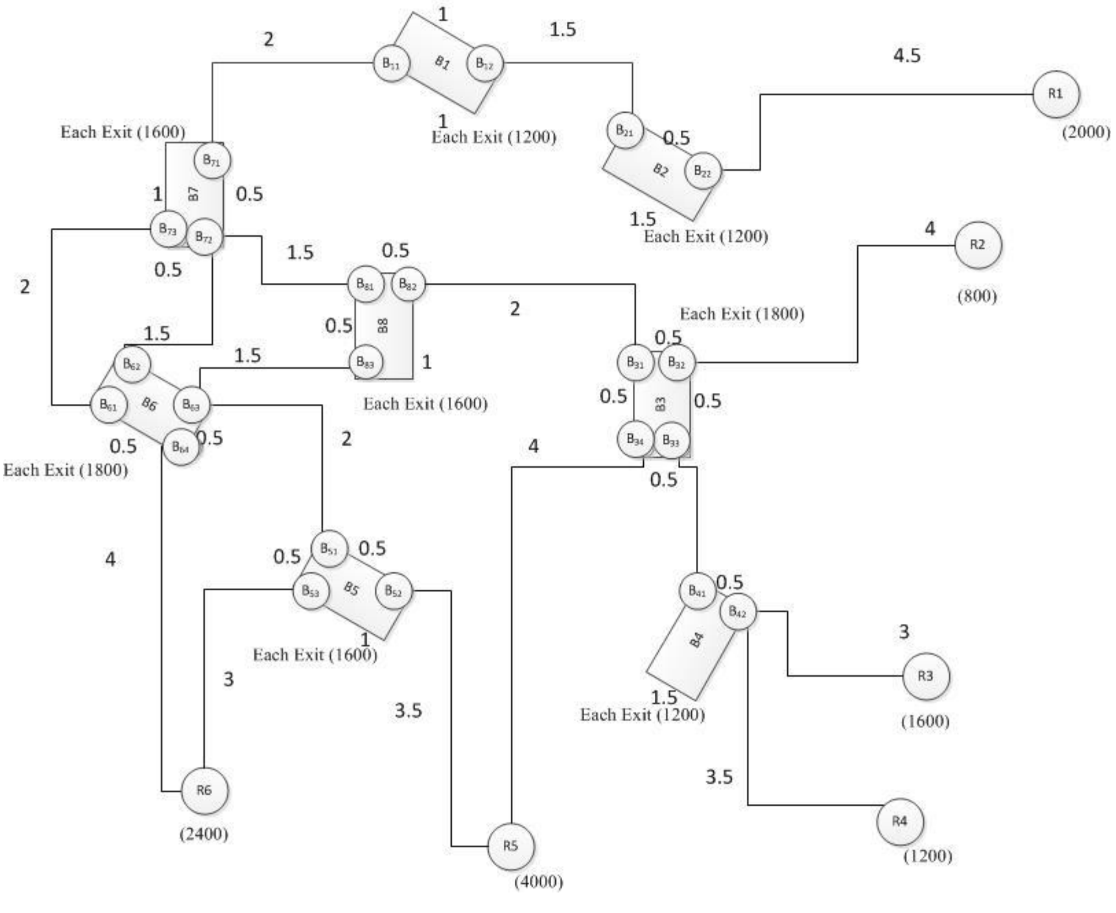

Figure 3. Numerical case study for evacuation planning

A numerical case study simplified from an emergency evacuation zone is given in Figure 3. There are eight blocks B1 to B8. Each block has a various number of exits. For example the jth exit in ith block is illustrated as B_{ij}. There are six identified safe areas R_1 to R_6. The value assigned to each path is the distance between the two ends of the path. For example the distance between B_{11} and B_{12} is 1 and the distance between B_{22} and $R_1$is 4.5. The population at each exit and the capacity at each safe area are shown in the round bracket. The path matrix is obtained by applying the Dijkstra algorithm and shown in Eq. 5. The element in the path matrix is the shortest distance between the exit and the safe area. For example, the most upper left element shows that the shortest distance between B_{11} and R_1 is 7.5, and the most bottom right element shows that the shortest distance between B_{83} and R_6 is 6.5. This matrix is updated every time the flood inundation model is executed to reflect the latest accessibility of all the paths. For example, the current distance between B_{62} and R_3 is 10.5, and the path is B_{62}>B_{63}>B_{83}>B_{82}>B_{31}>B_{32}>B_{33}>B_{41}>B_{42}>R_3. If the flood inundation model shows the path between B_{63} and B_{83} is not accessible, the shortest distance between B_{62} and R_3 will be changed to 11, and the path becomes B_{62}>B_{72}>B_{81}>B_{82}>B_{31}>B_{32}>B_{33}>B_{41}>B_{42}>R_3.

$$\begin{array}{cc}
 & \begin{array}{cccccc} R_1 & R_2 & R_3 & R_4 & R_5 & R_6 \end{array} \\
\begin{array}{c} B_{11} \\ B_{12} \\ B_{21} \\ B_{22} \\ B_{31} \\ B_{32} \\ B_{33} \\ B_{34} \\ B_{41} \\ B_{42} \\ B_{51} \\ B_{52} \\ B_{53} \\ B_{61} \\ B_{62} \\ B_{63} \\ B_{64} \\ B_{71} \\ B_{72} \\ B_{73} \\ B_{81} \\ B_{82} \\ B_{83} \end{array} &
\begin{pmatrix}
7.5 & 11 & 12 & 12.5 & 11 & 9.5 \\
6.5 & 12 & 13 & 13.5 & 12 & 10.5 \\
5 & 13.5 & 14.5 & 15 & 13.5 & 12 \\
4.5 & 14 & 15 & 15.5 & 14 & 12.5 \\
14 & 4.5 & 5.5 & 6 & 4.5 & 9.5 \\
14.5 & 4 & 5 & 5.5 & 5 & 10 \\
15 & 4.5 & 4.5 & 5 & 4.5 & 10 \\
14.5 & 5 & 5 & 5.5 & 4 & 9.5 \\
16 & 5.5 & 3.5 & 4 & 5.5 & 11 \\
16.5 & 6 & 3 & 3.5 & 6 & 11.5 \\
14.5 & 11.5 & 12.5 & 13 & 4.5 & 3 \\
14 & 11 & 12 & 12.5 & 4 & 3.5 \\
14.5 & 11.5 & 12.5 & 13 & 3.5 & 4 \\
12 & 10 & 11 & 11.5 & 7 & 5 \\
11.5 & 9.5 & 10.5 & 11 & 6.5 & 5.5 \\
12 & 9 & 10 & 10.5 & 6 & 5 \\
12.5 & 9.5 & 10.5 & 11 & 6.5 & 4.5 \\
9.5 & 9 & 10 & 10.5 & 9 & 7.5 \\
10 & 8.5 & 9.5 & 10 & 8.5 & 7 \\
10.5 & 9 & 10 & 10.5 & 9 & 7 \\
11.5 & 7 & 8 & 8.5 & 8 & 7 \\
12 & 6.5 & 7.5 & 8 & 8.5 & 7.5 \\
12 & 7.5 & 8.5 & 9 & 7.5 & 6.5
\end{pmatrix}
\end{array} \tag{5}$$

The optimal safe areas for each exit of all the blocks are represented as a decision matrix with the identical structure of rows and columns defined for the path matrix but substituting the shortest distance with the binary decision variable x_{ijk}. The format of the decision matrix is illustrated in Eq. 6. A Genetic Algorithm (GA) is applied to determine the decision matrix with the minimum value of Eq. 4. The evolution process of the GA is shown in Figure 4, where the value of the fitness function shown in Eq. 4 has been divided by 10^4. The resulted optimal safe areas and the corresponding blocks and exits are shown in Table 2, an alternative way to present the obtained decision matrix. Other evolutionary algorithms can also be applied in this application.

$$\begin{array}{cc}
 & \begin{array}{cccccc} R_1 & R_2 & R_3 & R_4 & R_5 & R_6 \end{array} \\
\begin{array}{c} B_{11} \\ B_{12} \\ \vdots \\ B_{83} \end{array} &
\begin{pmatrix}
x_{111} & x_{112} & x_{113} & x_{114} & x_{115} & x_{116} \\
x_{121} & x_{122} & x_{123} & x_{124} & x_{125} & x_{126} \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
x_{831} & x_{832} & x_{833} & x_{834} & x_{835} & x_{836}
\end{pmatrix}
\end{array} \tag{6}$$

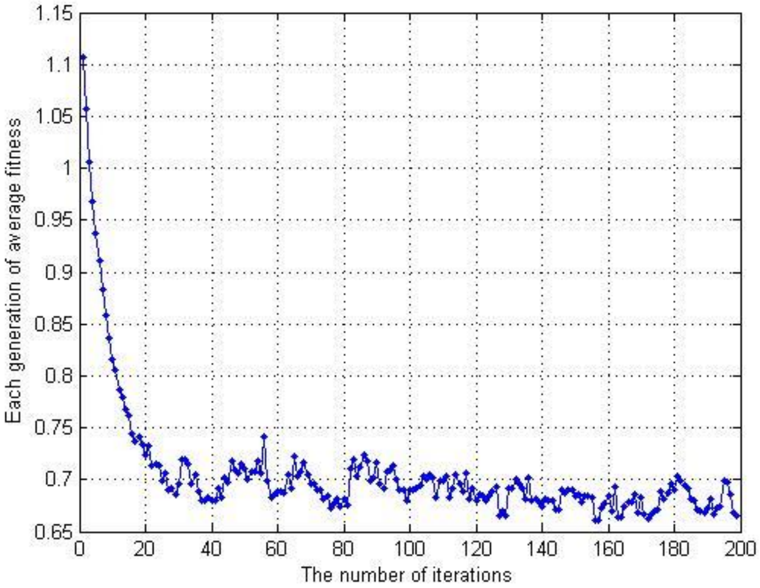

Figure 4. Evolution process of the GA

Safe areas	Blocks and exits evacuated from
R_1	B_{11}, B_{12}, B_{21}, B_{22}, B_{63}
R_2	B_{32}, B_{61}, B_{82}
R_3	B_{41}, B_{42}
R_4	B_{72}
R_5	B_{31}, B_{33}, B_{34}, B_{51}, B_{64}, B_{81}
R_6	B_{52}, B_{53}, B_{62}, B_{71}, B_{73}, B_{83}

Table 2. Optimal safe areas and corresponding blocks and exits

DISCUSSION

During the evacuation time, the flood will inundate certain area and make certain roads un-accessible. This dynamic characteristic should never be overlooked in the flood evacuation planning. This paper demonstrates a way to take the dynamic inundation into consideration. We do not claim the proposed three-step approach to be unique or without parallel, but the main contribution to knowledge made in this work is on the formation of the flood evacuation planning as a binary optimization problem. This work is based on an ongoing project and more results are expected to achieve in the near future.

Flooding is becoming the highest threat to British people. This work is expected to create major social and environmental impacts if success. This work aims to build a decision support tool for predicting the development of flooding and producing evacuation plan. The success of this tool will enhance the capability of flood defenses. The users of the tool include local authorities such as LFRS and local community risk register, and other decision makers. Furthermore, flooding may have significant environmental impacts as it can create landslides, black holes, destruct crops and cause pollution when mixed with industrial and domestic wastes, resulting in adverse impacts on the natural environment as well as human safety and health. The management of emergency responses to such impacts can be crucial in certain regional settings and under certain weather conditions. A system for flooding risk prediction and prevention, as well as evacuation planning would better prepare decision makers, especially under the uncertain climate future.

As a ongoing project there are still a number of issues to be addressed in the future. The work can be further improved with the views of practitioners or emergency mangers in regards to the proposed algorithms whether it is practical for them to use for decision making, i.e. the practical validity of the approach. It should be bear in mind that flood has very low time period for evacuation and any time-consuming algorithm could be not practical. Flood may cause many other problems such as landslide and pollution; therefore this work may also provide insights for research on cross impact of different risks and crises. If the proposed evacuation plan could be integrated into the management of other risks and crises, and be implemented on an emergency information system platform, the effectiveness would be greatly improved. The proposed approach might be only suitable for certain regions with certain weather conditions. These application constraints should be identified.

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