The Open Cybernetics & Systemics Journal, 2016, *10*, 83-90

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The Open Cybernetics & Systemics Journal

Content list available at: www.benthamopen.com/TOCSJ/

DOI: 10.2174/1874110X01610010083

RESEARCH ARTICLE

Research on Emergency Management of Urban Extreme Storm Floods Based on Strong Reciprocity

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Received: June 6, 2015 Revised: April 21, 2016 Accepted: May 10, 2016

Abstract: Urban storm floods have become one of the major natural disasters endangering city safety, economic and social development as well as life stability of urban residents. Due to urgent requirements of improving emergency management capacity, this paper introduces the strong reciprocity theory into emergency management of urban extreme storm floods (UESF), and sets up an evolutionary game model of emergency cooperation mechanisms. Simulations are performed in the example of Jingdezhen city, and the results show that the government strong reciprocity helps to promote emergency cooperation. Besides, rewards and punishment, strong ability of acquiring and processing information, extensive publicity and education can all improve emergency cooperation efficiency and effectiveness of UESF.

Keywords: Cooperation, Emergency management, Evolutionary games, Strong reciprocity, Urban extreme storm floods (UESF).

1. INTRODUCTION

An extremely heavy storm flooded Beijing, China on July 21, 2012 and stroke more than one million people with 77 deaths and huge economic losses. This disaster has drawn wide attention in China to UESF. It is not an occasional event. Actually, China has been seeing increasingly frequent UESF with global climate change and Chinese urbanization acceleration. For example, Guangzhou and Wuhan were flooded by extreme storms on May 7 and June 8 respectively in 2010, followed by UESF in Shanghai, Beijing, Haikou, and Jingdezhen in 2011, and Sichuan in 2013, Shenzhen and Guangxi in 2014, more than twenty cities nationwide in 2015, *etc*. These extreme storms have disabled cities and caused huge losses through flooding roads and even subways. Undoubtedly, cities are the center of population and wealth, and UESF have become one of the major natural disasters endangering city safety, economic and social development as well as life stability of urban residents. Since 1960s, there have been two streams in the literature on UESF. One of them focuses on simulation techniques of urban storm floods, for example, the STORM model [1], the SWMM model [2 - 4], the Walling ford model [5], the Stanford model [6], the Digital Water model, SSCM [7], UFDSM [8, 9], *etc*. [10 - 12]. The other is related to management of urban storm floods, either in technology or in policy. Technology examples include BMPs [13, 14], LID [15], WSUD [16], SUDS, and policy examples are administrative control, flood-discharge permits, flood-discharge fees, *etc*. [17 - 19]. However, emergency management mechanisms of UESF have been little examined [20]. Due to urgent requirements of improving emergency management capacity, this paper focuses on hydrological situations of urban China, and investigates mechanisms to promote emergency cooperation and to improve capacity and efficiency in emergency management of UESF, which is aimed to prevent cities from storm floods in China.

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A storm flood is the phenomenon that water in rivers surges due to storms, which is a highly complex natural event [21]. If storms flood cities, they cause losses in terms of wealth, properties and even human lives, which is a storm flood disaster. Storm floods happen every year, but they have not drawn much attention until those extreme cases have brought about huge losses. In hydrology and climatology, it is an extreme event if the hydrological situation notably deviates from the average level, which is unlikely to happen in statistics. In economic or social term, 'huge disasters' is used to describe large property losses or human injuries and deaths due to either natural disasters or human errors. Given these concepts above, this paper argues that UESF must characterize the following features: 1) Complexity, dynamics and uncertainty; 2) Low frequency of below 10% and causing large property losses, injuries and deaths; 3) Likely generating potential secondary disasters; 4) Beyond emergency management capacities and difficult to be dealt with by regular management, given economic and social situations and technological conditions of preventing and reducing natural disasters during a given period of time in a given city.

2. STRONG RECIPROCITY IN EMERGENCY MANAGEMENT OF UESF

Due to complexity, uncertainty, urgency and irregularity of UESF, emergency management is of great importance. In this paper, emergency management of UESF is that, for the duration of storm floods, potential measures of technology and management methods are properly taken, and available resources are efficiently organized, in order to: (1) monitor and manage storm floods; (2) protect and rescue people; and (3) minimize economic losses. Emergency management of UESF is a public good and is essentially a problem of collective action which requires cooperation. The tragedy of the commons, the prisoners' dilemma and the logic of collective action all suggest that in the presence of public goods, individual interests often conflict with common interests. Rational individual strategies lead to irrational collective outcomes. The underlying problem is free-riding. If one is not excluded to enjoy benefits contributed by others, the person has no incentives to make his own contributions and would prefer to be a free-rider. Even if some contribute, the outcome is far away from the optimum. This free-riding problem also lies in the emergency management of UESF which involves cooperation among multiple participators of disaster relief. Strong reciprocity is able to mitigate defection and free-riding and thus to improve collective well-being in the emergency management of UESF.

Strong reciprocity, suggested by Santa Fe Institute, is a new contribution to institutional evolution [22]. A large body of laboratory experiments consistently suggests that people tend to behave prosocially and punish antisocial behavior. This behavior is altruistic rather than selfish, which cannot be explained by the rational agent assumption in the mainstream of economics. This is because each individual is different from another in biological and social characteristics. Due to this het-erogeneity, individuals are intentionally motivated to promote social interactions for cognition. Frequent interactions develop prosociality and common interests, which makes cooperation possible. The theory of strong reciprocity argues that human groups maintain a higher level of cooperation than other species because a considerable fraction of human beings is predisposed to cooperate with others and punish non-cooperators, even at high prices which are not anticipated to be compensated. Obviously, the behavior of strong reciprocity has positive externalities. One question immediately arises: who is potentially a strong reciprocator in a group? Not every individual can be a strong reciprocator. A strong reciprocator must possess some good qualities in self-cognition or social-cognition, or some capacities to encourage other group members to press non-cooperators so that punishments can take effects. These good qualities are not innate but built up in intentional learning and practice and therefore professional strong reciprocators come into being. For example, the government is a legal and professional strong reciprocator which is called the government strong reciprocator [23]. The government is able to employ its legal power to punish defectors so as to promote cooperation.

The agents involved in emergency management of UESF include governments, emergency material suppliers, non-governmental organizations, the public, the media, the flood-stricken people, *etc*. As the provider of public goods and the manager of public affairs, the government is supposed to take active actions against storm floods. Moreover, compared to other agents, the government has much more advantages in material resources, human resources and organization capacities, so it should take principal responsibility as a leader. In emergency management of UESF, due to urgency and severity as well as limited resources and information, it is indispensable for the government to provide appropriate guides and to coordinate all agents so that the emergency rescue can be achieved in a short time. In this process,

- The government is a strong reciprocator. It is the decision-maker and policy-maintainer and its goal is to maximize the social welfare. It supervises the cooperation process and punishes non-cooperators while it is supervised by the public.

- Other agents are performers of emergency policies and their goals are to maximize their own payoffs. They defect at a probability and would be punished if caught by the government.

In emergency management, the government has more experiences than any other agent in strong reciprocity and thus is often self-motivated to design policies of emergency management. Besides, the government is driven to be in the leading position by its reputation and recognition from the public. The legal power of the government guarantees implementation of strong reciprocity. Put it differently, the government is able to maintain the cooperative behavior and to implement emergency policies. By punishing non-cooperators, a legal government, who is on behalf of the public in democracy, corrects defection and maintains cooperation. Because of long-standing existence of such a strong reciprocator, some cooperative and altruistic rules which are widely considered to help improve welfare of the whole society can be turned into policies by the government. In emergency management of UESF, the government plays the role as a strong reciprocator in two aspects: one is that the government sets up an emergency management system which well functions between levels and across sectors, and the other is that the government provide guides to coordinate agents and resources as a leader.

3. MODELING OF EMERGENCY MANAGEMENT OF UESF

The goal of emergency management of UESF is to maximize social responsibility through cooperation among agents coordinated by the government. This paper proposes that the government sets up an emergency cooperation mechanism of UESF based on strong reciprocity. The mechanism is characterized by communication, coordination, interaction and adaptation (Fig. **1**).

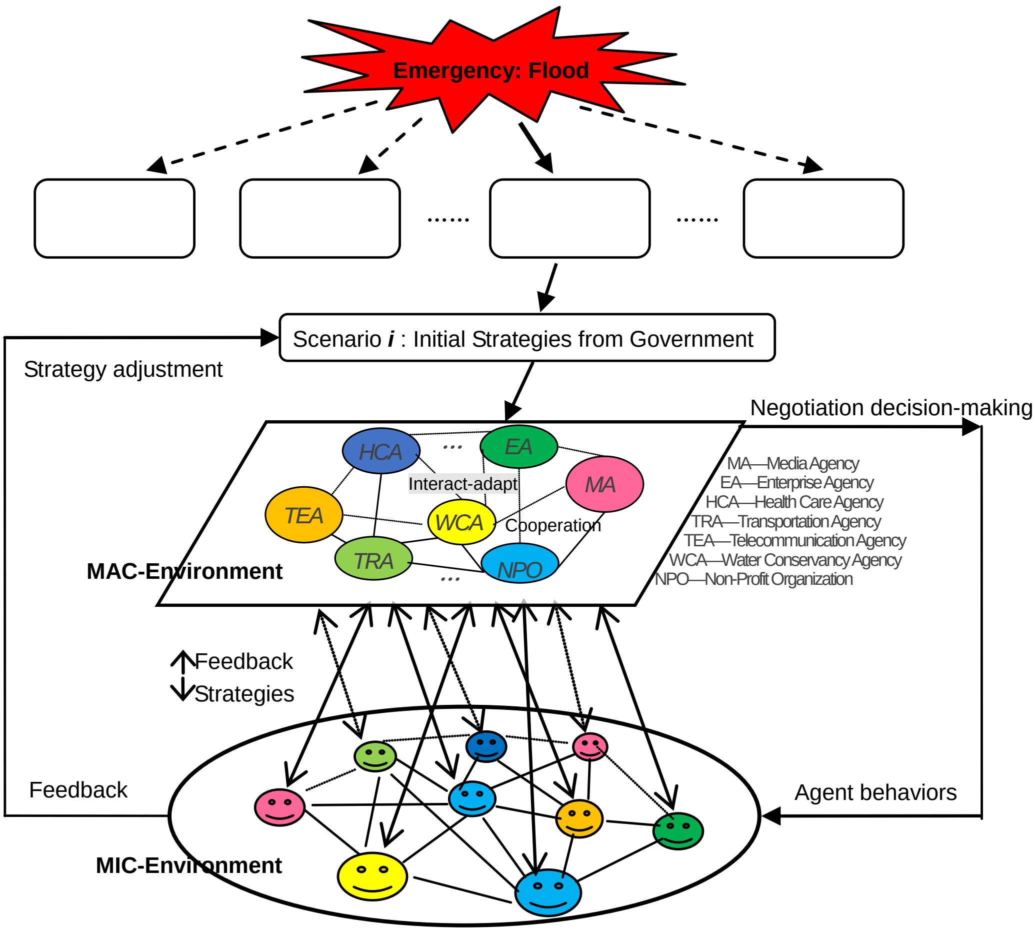


Fig. (1). Emergency cooperation mechanism of UESF.

Due to the uncertainty characteristics of UESF, there will have a variety of possible future scenarios of rainstorm, the best, the worst, the most likely, *etc*. The emergency decision-making process under each scenario is divided into two layers, the macro-level emergency decision-making model based on strong reciprocity, and the micro-level multi-agent co-evolution model. When scenario *i*, the initial strategies as strong reciprocity strategies are implemented in macro environment then the agent behaviors in the macro-level interact and adapt each other. The government is the main body of emergency management when coping with UESF in China, and plays a dual role: one is as a policymaker regulating the multi-agent behavior, and the other is as a main actor, which is involved in emergency action and providing public services. The government's coping strategy should not only emphasize emergency cooperation efficiency and effectiveness but also emergency timeliness, punishment and incentive mechanism, *etc*. The government has an obligation of regulation and supervision to emergency cooperative action process, and disposing non-cooperators, thus promoting them to participate in the emergency action and reach consensus. The strong reciprocity theory put forward by Gintis (2000) is that a strong reciprocator is predisposed to cooperate with others and punish non-cooperators, even when this behavior cannot be justified in terms of self-interest, extended kinship, or reciprocal altruism. A small number of strong reciprocators are enough to keep evolutionary equilibrium stability. Therefore, this theory is suitable for solving non-cooperative problems resulting from conflict of interest in macro-level emergency decision-making of UESF.

Within the regulation constraints of government, emergency participants are divided into different agents, such as medical and health agent, fire protection agent, traffic agent, rescue agent, water conservancy agent, enterprise agent, *etc*. Each agent plays a different role in the emergency cooperation system. At the same level of emergency cooperation process, there is a manager, who is directly responsible for flood, drought or water pollution management. Other agents on the same level work cooperatively around the manager. Each agent has its own behavior rules, and to make behavioral decision when it collect information from the outside world. After application of selected rules, the strength or fitness of rules will be modified, and the old rules are replaced by new rules, to complete an evolution process of exchange and mutation. Due to the changing external environment, the evolution process will continue to reach the pareto optimality, then to form a consensus decision-making plan and policy rules.

Assume that there are multiple emergency groups and each group consists of multiple agents in an emergency cooperation of UESF. Assumptions: (1) Utility maximization. In emergency management of UESF, agents maximize their own utility subject to limited time, information and capacity; (2) Bounded rationality. In complex and dynamic situations, agents are not able to make perfect decisions and predictions. Besides, they are not capable to completely share their knowledge and may have differing habits, beliefs and other factors. Thus, agents make decisions based on bounded rationality; (3) Heterogeneity. Agents are heterogeneous in two aspects: one is that they have different information; and the other is that they react differently. Agents make decisions based on their own knowledge and expectations of other agents; (4) Incomplete or asymmetric information. The emergency management of UESF is a systematic and dynamic task which is complex, urgent and uncertain, so information is often incomplete or asymmetric.

Each agent has two strategies: cooperation and defection. Agents who choose cooperation closely follow decisions from the upper levels, and then communicate and cooperate with other agents to finish the emergency task. In contrast, agents who choose defection don't work cooperatively either because they are too scary to get involved or because they intentionally take free rides. Thus, emergency cooperation of UESF is essentially the evolutionary equilibrium at which multiple agents of bounded rationality maximize their own utility subject to government regulations in the emergency situation of UESF.

Due to complexity, dynamics and irregularity of emergency management of UESF, this paper employs evolutionary game theory to set up a model of emergency cooperation. Agents are adaptive, that is, they are able to adjust their strategies according to environmental changes. To characterize this adaptive behavior in the model, three sets of learning rules are introduced [24]:

- The Reinforcement-based rule, that is, agents observe historical payoffs and then choose strategies which generated high payoffs in the past;
- The Beliefs-based rule, that is, agents infer future payoffs based on historical strategies of other agents and then choose strategies to maximize expected payoffs;
- The Experience-Weighted Attraction (or EWA) rule, that is, the reinforcement-based learning rule and the beliefs-based learning rule are weighted. It is a general learning rule which combines the first two rules.

After each stage of the game, agents obtain the following information: their own historical strategies and payoffs, others' historical strategies and payoffs, the environment information, *etc*. Agents adjust strategies based on historical and current information. As agents have different abilities to get information, this paper considers three adaptive rules:

- If agents have weak ability to get information, they adopt the reinforcement-based rule. Agents infer future payoffs based on their own historical strategies and payoffs, and have no information of others;
- If agents have moderate ability to get information, they adopt the beliefs-based rule. Agents can get information of others and infer future payoffs based on historical strategies and payoffs of others;
- If agents have strong ability to get information, they adopt EWA rule. Agents have information of their own historical strategies and payoffs and of others' historical strategies and payoffs as well.

The evolutionary model of emergency management of UESF is as follows. When the individual interest conflicts with the collective interest, the agent would choose defection. Meanwhile, due to the animal effect, more agents would defect and take free rides. This defection causes huge losses in the emergency management. To improve efficiency and effectiveness of emergency management, strong reciprocity is necessary to be introduced. A strong reciprocator has the power to regulate collective behavior and punish non-cooperators. The government is in the position to be a strong reciprocator to lead emergency management of UESF. To make the model tractable, this paper considers two groups.

a. Players. Let A and B denote two groups which make independent decisions. A_i (i= 1,2,...n) and B_j (j= 1,2,...m) denote agent i in group A and agent j in group B respectively. Their strategy spaces are represented by S_{Ai} and S_{Bj}.
b. Strategies. With the government strong reciprocity, there are three learning rules: 1) The reinforcement-based rule; 2) The beliefs-based rule; 3) The Experience-Weighted Attraction rule. Meanwhile, each agent has two strategies: Cooperation and Defection.
c. Payoffs. The payoff of each agent in two groups is denoted respectively by U_{Ai} (S_{Ai}, $S\text{-}_{Ai}$) and U_{Bj} (S_{Bj}, $S\text{-}_{Bj}$) where S_{Ai} and S_{Bj} represent strategies chosen by A_i and B_j while $S\text{-}_{Ai}$ and $S\text{-}_{Bj}$ represent strategies chosen by other agents excluding A_i and B_j. Due to the government strong reciprocity, the agent who defects would be punished and thus the payoff is reduced by p while the agent who cooperates would be awarded and the payoff is increased by r. The payoff matrix is shown in Table **1**.
d. Matching rules. At time t(t = 1,2,...T), agents in groups A and B match each other randomly once.

Table 1. Payoffs of the evolutionary game with the government strong reciprocity.

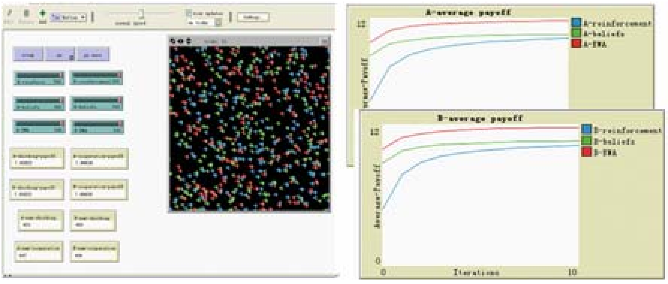
Scenario *i*		An agent in group B	
		Cooperation	**Defection**
An agent in group **A**	Cooperation	$U_{\text{Acc}} + r$, $U_{\text{Bcc}} + r$	$U_{\text{Acs}} + r$, $U_{\text{Bsc}} - p$
	Defection	$U_{\text{Asc}}\text{-}p$, $U_{\text{Bcs}} + r$	$U_{\text{Ass}}\text{-}p$, $U_{\text{Bss}}\text{-}p$

4. SIMULATIONS

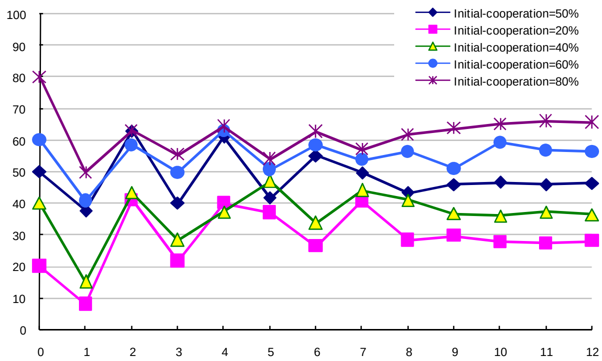
To make the simulation more specific, this paper takes Jingdezhen city as an example. Jingdezhen, one of the four most renowned ancient cities in China, is located in foothills down the Chang River in Jiangxi Province. Its annual rainfalls are 1763.5mm on average compared to 630mm in the whole country, and it is one of the three storm centers in Jiangxi Province. Thus it is frequently and severely stricken by storm floods. The simulation takes the UESF on June 30, 1999 as the settings. Jingdezhen had heavy rains from 21 to 30 June, and the total rainfall was 396.3mm. Zhushan and Changjiang were the worst-hit areas. There are many emergency agents but, for simplicity, this paper only considers three types of agents:

- The first is two rescue groups who are respectively from Zhushan and Changjiang. Each group has multiple agents and they help to rescue people and transfer wealth.
- The second is government agents who monitor and control the whole system. The government agents regulate, manage and supervise the emergency, and design emergency policies and strategies.
- The third is environment agents which include the natural environment and the flood situations.

The simulation is undertaken on Netlogo on Windows. In the simulation world, there are three types of agents: Turtle, Patch, and Observer. Patch denotes the environment agent and Turtles denotes the rescue agents, and Observer is the government agent. Given the situation of Jingdezhen and heterogeneity of agents, assume that each if the two rescue groups from Zhushan and Changjiang has 900 agents, and each third adopt the reinforcement-based rule, the beliefs-based rule and the EWA rule. As this paper is only interested in the relative payoffs, the unit of payoffs is normalized to one. Assume that the payoffs of different strategy combinations of Zhushan and Changjiang are as follows: $U_{Acc}= U_{Bcc}=$ 4, $U_{Acs}= U_{Bcs}= 2$, $U_{Asc}= U_{Bsc}= 6$, $U_{Ass}= U_{Bss} = 0$. The payoffs are in total including reputation and non-material rewards. The simulation results are shown in Figs. (**2** and **3**). Fig. (**2**) shows simulation results of different learning rules and initial beliefs without strong reciprocity while Fig. (**3**) shows simulation results with strong reciprocity.



(a) with different learning rules



(b) with different initial beliefs

Fig. (2). Average payoffs of emergency cooperation.

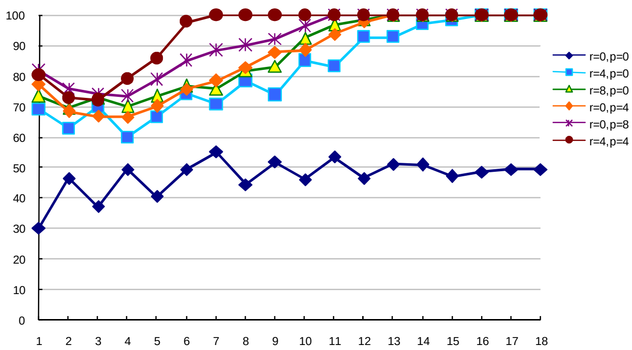


Fig. (3). Average payoffs of emergency cooperation with different strong reciprocity policies.

From the average payoff in Fig. (**2a**), the EWA learning rule is better than the beliefs-based learning rule. This suggests that both information acquisition and learning ability have significant impacts on cooperation evolution. The stronger the ability of obtaining and processing information, the higher the payoffs. Initial beliefs refer to prior prediction of strategies, which is denoted by population percentage of two strategies at t=0. The percentage of agents choosing cooperation at each stage is used to measure cooperation evolution. The more players choose cooperation, the better the emergency cooperation. In contrast, the more players choose defection, the worse the emergency cooperation. From Fig. (**2b**), it can be seen that initial beliefs play an important role in cooperation evolution. If more players choose cooperation at the initial time, agents tend to cooperate. If more players choose defection at the initial time, agents tend to defect. These rules Match with the actual situation of UESF in 1999. The well-trained soldiers were more inclined to cooperation, who followed the EWA learning rules and had strong ability of information acquisition and learning. The urban residents in Jingdezhen were inclined to cooperation, who lived in a high risk area and had experience in fighting against floods. The public who had more experiences and disaster-relief abilities/beliefs preferred to cooperation.

Fig. (**3**) presents results of government strong reciprocity in emergency management of UESF. It can be seen that: (1) Policies of strong reciprocity such as rewards and punishment can effectively improve cooperation and maintain order, and they are more effective than changing initial beliefs and learning rules. (2) The larger rewards and punishment, the earlier the results converge and the more efficient the cooperation. (3) Punishment can improve cooperation and is more effective than rewards. (4) Combination of rewards and punishment is better than alone.

In fact, these are consistent with historical experiences. Several heavy floods of the past in Jingdezhen were defensed successfully, such as on June 30, 1999, July 15, 2010, August 12, 2012. The successful experiences included high attention of leaders and unity command, quick response and scientific scheduling, public participation and solidify cooperation, and forceful supervision.

To summarize, emergency cooperation is affected by strong reciprocity policies such as rewards and punishment, ability of obtaining information and learning, initial beliefs, *etc*. Therefore, suggestions are as follows:

- The government should play a stronger role in leadership and coordination of preventing and reducing losses from UESF.
- A completely-constructed and well-functioning system of emergency management should be established in which each sector is responsible for its specialized work while in close cooperation across sectors.
- Responsibilities should be specified unambiguously and categorized and classified in detail. Rewards and punishment are attached along with responsibilities. Meanwhile, information should also be exposed to the media and the public for supervision.
- Hydrological information systems should be improved so that information can be shared across sectors and collected from sectors to the upper levels or circulated from sectors to the lower levels.
- The public should keep alert of storm floods. The government and the community can make use of the media to improve both awareness and skills of the public on preventing losses from storm floods.

CONCLUSION

Urban extreme storms have flooded China increasingly frequently but their emergency management has little been investigated. This paper has introduced strong reciprocity into emergency management of UESF and examined cooperation among multiple agents. As human behavioral is complex and hard to be quantified, together with limited data availability, it is difficult to do research on emergency management. The emergency management of UESF is a multi-disciplinary topic and it is worth being explored further in the future.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

ACKNOWLEDGEMENTS

This work was supported by the National Natural Science Foundation of China (71303074,71433003, 71303180), the major program of the National Social Science Fund (12&ZD214), Research Fund for the Doctoral Program of Higher Education of China (20120094110018), the Natural Science Foundation of Jiangsu Province, China (BK20130242, BK20131135), and the Fundamental Research Funds for the Central Universities (2013B18914).

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