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Plotting earthquake emergency maps based on audience theory

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ABSTRACT

Emergency response and rescue is an important way to mitigate the loss caused by earthquakes. Various maps containing information about earthquakes provide effective guidance and references for individuals undertaking such action. However, the production of earthquake emergency maps aimed at the "right" user in an effective manner is challenging. In this study, we focus on two questions: (1) Who are the users of earthquake emergency maps and what information do these individuals need? (2) How can the maps be produced quickly and efficiently according to the requirements of different users? To answer the first question, we classify the users into four categories under the guidance of audience theory: earthquake emergency decision-makers, auxiliary decision-making technicians, emergency rescue workers, and the public. The map contents are also described according to the requirements of different audiences. We depict the methods used for representation in such earthquake emergency maps for different audiences, which places a foundation for answering the second question. Following that, a template-matching mapping method is proposed for the rapid production of emergency maps, including two phases: before the earthquake templates of emergency maps for different audiences are prepared; after an earthquake, the template is updated with information from seismic models, so that the emergency maps are automatically plotted. Finally, a case study is provided to verify the mapping method. We conclude that the application of audience theory and the related template-matching method for map production not only answers the two questions but also will benefit the emergency mapping of other disasters.

1. Introduction

Earthquakes are natural disasters that usually lead to numerous deaths and injuries, and extensive economic loss [1]. China lies between the circum-Pacific seismic belt and the Eurasian seismic zone and has suffered from some of the most severe earthquake disasters in the world [2]. For example, the Wenchuan earthquake in 2008 caused 69,227 deaths, 374,643 injuries, 17,923 missing people, and more than 10,000 square kilometers of severe damage [3]. A method for the accurate short- and medium-period prediction of earthquakes has not yet been discovered. Earthquake emergency response and rescue is an important means by which mitigation of such disasters can take place after an earthquake, and the effectiveness of this system has often been verified [4]. After the occurrence of an earthquake, maps that include information pertaining to an earthquake and the associated possible disaster can provide a foundation for effective emergency search and rescue, and therefore play an important role in the emergency response and rescue process. These maps are therefore essential thematic maps that display the various types of information needed for earthquake emergency command and rescue.

Earthquake emergency maps are important to the leaders of rescue operations and the staff members of governments. These individuals can intuitively understand the information regarding an earthquake disaster, and carry out rescue operations in a timely manner [5]. The three days following an earthquake are known as the "golden period of emergency rescue"; after this time the number of dead sharply increases [6,7]. In China, the government needs approximately 24 h to collect and send emergency rescue materials to a disaster area, which is usually located in the mountain regions of Southwest China. This means that the governmental lead needs to make rescue decisions within half a day following an earthquake. In such a situation, emergency maps that include useful information are crucial in aiding such decision-makers.

However, the means by which useful maps in earthquake emergencies can be produced in an effective manner is challenging. Two questions concerning earthquake emergency mapping are discussed in this paper. Many people are involved in emergency response and rescue.

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Different participants have different requirements for earthquake emergency maps. Therefore the first question is concerned with the information required by the different participants.

Much of the information generated and collected during the earthquake emergency process is characterized by complexity, timeliness, hierarchy, incompleteness, and dynamic changes over different periods. The second question is therefore concerned with how earthquake emergency maps can be rapidly produced that are easy to understand and meet the demands of different participants.

Several investigations have already focused on this issue, in which some discuss the symbology that helps different participants understand disaster information. Ute [8] analyzed the importance of the symbology used on emergency maps for sharing information and suggested a framework for emergency mapping symbology. Li et al. [9] leveraged Pierce's Triple Symbol Model for the semantics of emergency symbols and discusses the characteristics, principles, and theoretical framework of an earthquake symbol system. Robinson et al. [10] developed a database of symbols for mapmakers to share, relaying information concerning symbols for use in emergency management on the Internet. This database allows users to browse symbols using parameters such as keywords or category tags. Akella [11] focused on how human factors can be used to improve the design and comprehension of map symbols for emergency mapping and used the American National Standards of Federal Geographic Data Committee Homeland Security Working Group (FGDC HSWG) for this. Bianchetti et al. [12] addressed the importance of using similar map symbols for emergency management, which helps to exchange information between different individual countries and government agencies. The paper evaluates the influence from two sets of map symbols (American ANSI and Canadian EMS) on the conceptions of map users. Kostelnick and Hoeniges [13] summarize the important issues in developing a generic crisis map symbology, including symbol taxonomies, standardization, and information sharing. These studies provide good references for the production of earthquake emergency maps. However, the actual production of earthquake emergency maps includes more than symbols.

In order to improve the speed of mapping, the earth observation system (EOS) technology has been adopted to make emergency maps. With the development of remote sensing satellites in recent years, the EOS-based emergency mapping capacities have steadily increased and widely used in many natural disasters [14–16]. Boccardo [17] describes the use of state-of-the-art remote sensing technology for emergency mapping. Xue and Zhang [18], analyzed the earthquake emergency mapping process, described key problems with the use of images produced via remote sensing, and designed software for use in emergency mapping. Wegscheider et al. [19] conducted a similar study on the usage of EOS technology to achieve rapid earthquake emergency mapping and demonstrated the application of this technology with regards to the 2010 Haiti earthquake and the 2011 Turkistan earthquake. Girres [20] aimed at improving the efficiency of emergency mapping, proposed a "hazard-based" satellite image comparison method by considering the spatial diffusion characteristics of the hazard and realized the method using GIS software. Regarding the Gorkha earthquake in Nepal, Ge et al. [21] discuss the near real-time mapping activities of SAR satellites. Similar studies have been carried out concerning disaster loss assessment for emergency mapping through the use of remote sensing images [22]. Although the EOS-based emergency mapping technology has achieved good results in many real disasters, it still has challenges with a relatively long time to obtain and prepare satellite images (about 2 days on average) and make emergency maps from them (about 6–8 h) [14].

Geographic information system (GIS) technology is also used in emergency mapping. Xi et al. [23] presented a model for earthquake emergency mapping based on ontology and developed an emergency mapping system. Chen et al. [24] and Wang and Song [25] discussed the use of a map-template as a method for the quick production of emergency maps. Shi [26] carried out similar studies by analyzing the mapping models for emergency maps of natural disasters and introduced a workflow for emergency mapping based on map templates.

Recent studies have therefore made attempts to improve the emergency mapping of natural hazards but further investigation, specifically concerning the mapping of earthquake disasters, is required. Earthquakes are more complex than other natural disasters [27]. Many professional seismic models need to be used in the production of earthquake emergency maps, such as models for the estimation of the number of deaths, models of the field of seismic influence, and models for the estimation of building damage [28–31].

Many individuals and organizations participate in earthquake emergency response and rescue, in which cooperation and coordination of different participants are crucial [2]. In order to support cooperative and coordinative actions, various participants within different periods have diverse requirements for emergency information. Following the 2015 Gorkha earthquake in Nepal, Williams et al. [32] discuss issues associated with what information on landslides is relevant to whom and when, and how this compares with what science is able to provide. They also assert the value of information on landslides evolves rapidly as a disaster response develops. Li et al. [33] try to understand the information dissemination process in Yiliang Earthquake with social media and reveal the dynamic characteristics in the propagation of disaster-related information. However, the direct studies on information requirements for different participants in plotting earthquake emergency maps need further investigation.

Generally, in order to cope with the two questions, audience theory is introduced to recognize the identity of the participants in earthquake disaster response and rescue, to try and answer who the users of the earthquake emergency maps are, and to understand what information is needed to plot the maps. The related mapping method based on the map-template matching method is also introduced. The paper proceeds as follows to achieve the above contributions. In Section 2, we describe the audiences using earthquake emergency maps. In Section 3, we describe the contents of the earthquake emergency maps that are required by different audiences and the methods for representation. In Section 4, we present a template-matching method to realize the mapping of emergency maps for different audiences. In Section 5, we provide a case study to demonstrate the application of these mapping methods. Finally, in Section 6, we offer conclusions and suggest directions for future research.

2. The audiences of earthquake emergency maps

In this section audience theory is introduced, to explore the objectives for the application of the emergency maps, named as the audiences of the earthquake emergency maps. The application of audience theory helps to understand who the users of the maps are, what kinds of maps are needed, and what information should be included in the maps.

2.1. Audience theory in information dissemination

The word "audience" refers to the readers, listeners, and spectators that receive information [34,35]. The audience is an important concept in the study of mass media. The study of the history of mass media always includes the study of the history of an audience. The different genres in audience study can be classified into three categories. "Structured" audience study is an early type of audience study [36]. Relying on demographic data, the main purpose of the research is to analyze the composition of the audiences and then reveal the relationship between the media and the mass users. The results of such research are widely used to investigate media ratings. "Behavior" audience study aims to explain and predict the choices of an audience, together with the reactions and the effects of the media. From the perspective of audience choice, use, opinions, and attitudes, this type of study can be used to improve and enhance the effectiveness of media communication, explain the influence of media on the masses, and predict the possible behavior of an audience. For example, Starkey [37] uses sampling techniques to produce audience research data in cultural consumption for the broadcasting industries, for the programmers and advertisers who need detailed 'knowledge' about their audiences. The purpose of "cultural" audience study is to understand how the audience "decodes" the media. This kind of study is often used to understand the meaning of the received media content and its application in context.

Compared to common information, maps are graphical information presented in symbolic form. A map is a combination of the spatial-temporal state of surface features and phenomena [38–40]. In essence, a map is a medium used for the dissemination of information. The information produced by maps has graphical and mathematical characteristics as compared with other media. When an audience (user) reads and analyzes a map, the graphical information relayed by the map is acquired and the related knowledge obtained, meaning that the uncertainty of an audience with regards to relevant topics will be avoided.

Map transmission is the process of transmitting spatial information through maps, using a graphical form of spatial information. Regarding audience theory, there is also a process for the transfer of the information within a map to the application of a map. The designers and authors of maps produce information. The recognition of mapping objects is processed (i.e. selected, classified and simplified) and coded in symbols, then the information is transferred to the users through the map as a channel, in which users are the map audiences. Audiences can then retrieve the information contained in a map through recognizing and decoding the symbols.

2.2. Audiences of earthquake emergency maps

The division and selection of audiences using earthquake emergency maps are the basis of earthquake emergency mapping. In another word, we first need to answer "who are the target audiences/users of the emergency maps?" in accordance with the audience theory, and then "what the categorization of the audiences is?". To answer the first question, we are aware of earthquake emergency response and rescue is complex that many individuals and communities are involved in. So we preliminarily consider the participants in earthquake emergency response and rescue as "target audiences" of the earthquake emergency maps.

The audience categorization has developed with the progress of contemporary media such as the wide usage of social media. In the mass media audience field, audience division is related to "audience segmentation/audience fragmentation" phenomenon that describes the process of partitioning mass audiences into smaller and smaller segments [41]. The models of audience segmentation have experienced four generations: "unitary model, "pluralism model", "core-periphery model", "breakup model", been stepping into the "individualization model" and created the scenario of "autonomous audience" [41,42].

Differing with mass media, the earthquake emergency maps delivering seismic related information help communication with different participants in the disaster response. The recognizing and dividing of the disaster audience not only consider the audience segmentation model but more important is following the knowledge of disaster management. Saputro [43] explores the responders of those participants, tries to understand who are they and why their attentions are changed. Then study on disaster communication of different participants has been done from the audience perspective and reveals the audience's experience from collective attention to collective actions.

For communication purposes of the participants, Haddow and Haddow [44] divide the audience in disaster communications into four categories: public audience, elected officials and community leaders, partners and stakeholders, and the media based on the four phases of emergency management—mitigation, preparedness, response, and recovery. A complex categorization has been proposed in which basic emergency management audiences are classified as the general public, disaster victims, business community, media, elected officials, community officials, first responders, volunteer groups [45].

In our study, we continue to ask "how do they get earthquake emergency information?", "what are their profiles?". Then we try to find the answers from Chinese earthquake emergency response and rescue system, which is formed by related Chinese laws and regulations, such as the "Law of the People's Republic of China on Protecting Against and Mitigating Earthquake Disasters",[1] "Chinese National Earthquake Emergency Plan"[2] and "Earthquake Emergency Plan of China Earthquake Administration".[3] In the system, the organizers and participants and their responsibilities of the earthquake response and rescue are set, which provides good guidance to recognize target audiences. For example, earthquake emergency response and rescue headquarter is in charge of the entire activity. Other response and rescue groups need to be formed after an earthquake, such as the aftershock-monitoring group, disaster information group, and rescue group. Thus, we divide the audiences of earthquake emergency maps into four categories: earthquake emergency decision-makers, auxiliary decision-making technicians, emergency rescue workers, and the public.

Earthquake emergency decision-makers (Leading group): Earthquake emergency decision-makers are the core of an entire earthquake emergency rescue organization. According to the Chinese earthquake emergency response and rescue system, decision-making is usually carried out at the headquarters for earthquake disaster mitigation, which is composed of the leaders of the related governmental departments. The process of decision-making in earthquake emergency command requires the support of various related maps. The decision-makers are therefore an audience for earthquake emergency maps. These audiences have rich administrative experience but little professional knowledge in the field of the earthquake emergency.

Much of the information related to earthquakes and disasters is not fully understood by this audience, such as seismic geological structure and seismic movement. Earthquake emergency maps represent information for decision-makers in the form of graphics and symbols, which can assist them in understanding. The maps not only include basic information for earthquake emergency decision-makers but also include the auxiliary decision-making suggestions provided by experts in the field of the earthquake emergency.

Auxiliary decision-making technicians (Experts in the field of earthquake emergency): This part of the audience refers to the experts; technical personnel involved in earthquake emergency response and rescue. The main work undertaken by this sector is the provision of decision-making references and technical support to the earthquake emergency commanders and decision-makers. This kind of audience is required to dynamically monitor and analyze the development of an earthquake and the subsequent disaster information over the entire period of the earthquake emergency. An estimation of the impact from an earthquake needs to be understood within a suitable timeframe, according to the limited information collected, and various suggestions are required to be published within this timeframe. Under these circumstances, earthquake emergency maps are very important. Information concerning a disaster in plain text, such as 'three people died in a certain township', is far less intuitive for use than a map of the distribution of a disaster. In addition to grasping the distribution and severity of a disaster, such a map can also provide in-depth information about whether villages and townships are at the edge of a disaster area or in the meizoseismal area, as shown in Fig. 1.

Emergency rescue workers (Rescuer): This audience is made up of the emergency rescue workers who carry out the actual rescue jobs, and reduce casualties through on-site action. The support from thematic earthquake emergency maps will improve the effectiveness of such

[1] http://www.tibetsafety.gov.cn/sitesources/xzajj/page_pc/zcfg/fl/articlec619147bb5c7468498d1a1eb40ebc2ec.html, access on Oct. 12, 2019.

[2] http://www.gov.cn/zhuanti/2006-01/12/content_2615957.htm, access on Oct. 12, 2019.

[3] http://dzj.baoji.gov.cn/news_look1.asp?id=2572, access on Oct. 12, 2019.

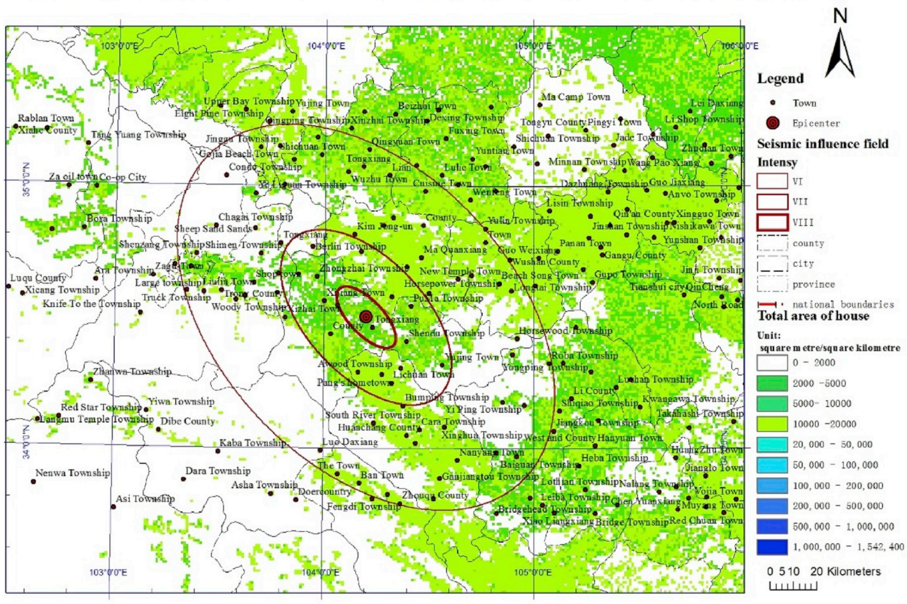

Fig. 1. Representation method of earthquake emergency map for professional audiences (using "distribution map of house area in disaster area" as an example).

rescue. Map information related to these jobs includes traffic damage caused by earthquakes, the distribution of medical and rescue resources, and the locations where the burial of a population is concentrated, among many other uses.

The public (News media): Generally, the public seems unsuitable as a kind of audience of the emergency maps in accordance with the audience theory. Herein we use the words to represent people who are concerned with the disaster and its development after an earthquake. The news media is widely considered as the representative of the public, through numerous news reports on the disaster, news media provides a significant amount of information about the earthquake to the general public.

As a Chinese old saying "one picture worth a thousand words" depicts the importance of pictures to express the information. A map is convenient to provide the public with such information so that the disaster situation can be understood and to avoid panic concerning the earthquake. Indeed, maps and GIS are already widely used to better understand and respond to a natural disaster [46]. Good results can be achieved in presenting earthquake information for this audience by way of earthquake emergency maps [24,47]. This audience has a higher demand for earthquake emergency maps after the occurrence of the earthquake. The public is numerous in compared with the other audiences. Ease of understanding and simple visualization of maps are therefore crucial.

3. Earthquake emergency maps for different audiences

3.1. Contents of earthquake emergency maps

Different audiences have different needs with regard to earthquake emergency maps. It is necessary to study the demand for the required contents of earthquake emergency maps corresponding to different audiences, which is the foundation for production. The contents required by the different audiences are presented in Table 1, with the following details:

(1) **Decision-makers during earthquake emergencies:** The main demands of earthquake emergency maps for this audience are to meet the requirements of earthquake emergency command. According to the Chinese earthquake emergency response and rescue system, the most important work of decision-makers after an earthquake is focused on three aspects: grasping the basic information of the disaster area; understanding possible damage and losses, and aftershock information; and making arrangements for quick response and rescue. So related maps are needed for them, including:

a. Maps used for decision-making, such as maps suggesting traffic control, maps detailing possible routes to be used for rescue, maps assessing the losses resulting from an earthquake, maps of the distribution of potential secondary hazards, and maps of key government objectives concerning preservation.
b. Maps relaying on-site information about a disaster, such as maps detailing the area where an extreme disaster has occurred, maps concerning casualty information, maps of building losses, and maps relaying any losses of infrastructure.
c. Earthquake information maps, such as epicenter distribution maps and maps estimating the distribution of seismic intensity.
d. Fundamental physical geography and socio-economic maps, such as maps of administrative regions in disaster areas, maps detailing the distribution of important river systems, maps of the population distribution in a disaster area, GDP distribution maps, and ethnic distribution maps.

Table 1
Content needs of emergency maps for different audiences.

Audience type	Cartographic content category	Demand level
Earthquake emergency decision-makers	Maps for decision-making, on-site disaster information maps, earthquake information maps	High
	Fundamental physical geography and socio-economic maps	Normal
Auxiliary decision-making technicians	Maps of physical geography and social economy, earthquake information maps, on-site disaster information maps	High
Emergency rescue workers	Maps of search and rescue objectives, maps of search and rescue support, maps of on-site rescue command	High
The public	On-site disaster information maps, earthquake information maps	Normal

Because of the existence of the black-box period immediately following an earthquake [4], on-the-spot information concerning the extent of a disaster is very scarce, which means that modeling is often used to estimate the extent of a disaster instead of on-site information in earthquake emergency response and rescue [48]. We consider such estimated disaster information and its corresponding map as a decision support map. The four types of maps are together supporting decision-makers, in which some maps are in high demand as shown in Table 1. Because these maps are fundamental and provide direct support to make decisions.

(2) **Auxiliary decision-making technicians:** The audience needs to process, reorganize, and map various types of information obtained from different sources, including auxiliary information, professionally developed models, and the experience of experts. Therefore, some kind maps listed below are highly required that provide necessary information to the technicians.
   a. Maps of the physical geography and social economy within a disaster area. Unlike the emergency decision-makers, this audience needs more detailed and professional maps such as DEM (Digital Elevation Model) maps, maps of the distribution of annual rainfall, and maps detailing the distribution of buildings.
   b. Earthquake information maps. Similarly, compared with the needs of the decision-makers, the requirements are more professional and detailed, such as maps of the geological structures in a disaster area, maps detailing where tremors have taken place, historical earthquake maps of a disaster area, and maps of aftershocks.
   c. Maps containing information concerning the on-site disaster, such as maps of the distribution of landslides or of debris flow caused by the earthquake.

(3) **Emergency rescue workers:** The emergency rescue workers are concerned with information related to the rescue. The map contents required by the audiences are therefore different than that of other earthquake emergency audiences. The corresponding maps in high demand focus on rescue-related actions, including:
   a. Maps of the objectives of a search and rescue operation, such as a map of the location of buried members of a population.
   b. Maps of search and rescue support: such as airports, docks, station maps, traffic maps, and traffic damage maps, maps detailing the location of material stocks, and maps of temporary material hubs.
   c. Maps of on-site rescue commands, such as the location of the various levels of rescue command headquarters, and maps of the actual rescue situation.

(4) **The public:** The public also needs to know about the development of an earthquake and receive information concerning a disaster for the reason of personal safety. The required content in public emergency maps includes information concerning the earthquake itself, information about an on-site disaster, and information detailing the progress of emergency rescue. The demand level of the public is unlike other audiences, since professional maps may be neither necessary nor easy to be understood for them. Relatively, representing the information in a more intuitive way is important to them.

3.2. Representation method of earthquake emergency maps

The required maps of audiences need different methods of representation and emphasis. An earthquake emergency map is a kind of thematic map, and the method used for representation in thematic maps will require the provision of references to the methods used. Cartographic methods for the representation of different kinds of map features (i.e. point, line, and polygon) can be used in earthquake emergency maps. Thematic mapping methods are employed for the three types of the audience: the decision-makers, the technicians, and the rescue workers. Detailed methods used in different earthquake emergency maps are presented in Table 2. We select representation methods according to the formats (vector vs raster) of different thematic features. For example, the kilometer grid method is used for raster features. Representation methods of vector features are decided according to their geometry types, for example, the line symbol method is selected to line features.

As an example, Fig. 1 shows a map of the building distribution in kilometer grid format within an estimated seismic intensity field. The map aims at providing basic information to the technicians to help them understand the building density in a disaster area. The seismic intensity fields are estimated using a model of the magnitude–intensity attenuation relationship, which will be introduced in section 5.

The public audience is quite different from the other audiences. Representing earthquake emergency information with the use of thematic maps may be difficult for the general public to understand. A direct and simple representation method is required for this audience. The China Earthquake Administration (CEA) and its sub-research institutions have explored different methods to achieve a useful means of relaying disaster information to this audience, eventually producing the “explanation of an earthquake in pictures” method which relayed information concerning the Ludian earthquake for use by the public and news media as shown in Fig. 2. The document produced is much like a poster, merging pictures and text to represent the earthquake information, in which the text provides a supplementary explanation concerning the obscure and professional thematic maps and pictures. This method was successful and accepted by the public. However, the “explanation of an earthquake in pictures” is a new idea. It has no specifications, which needs to be improved and the CEA will further work on it.

4. Mapping earthquake emergency maps

4.1. Template-matching mapping method for earthquake emergency maps

Using audience theory, we answer the first question of who the users of the maps are and what content is required. There are three problems that need to be handled speedily in order to generate earthquake emergency thematic maps. The first and the most important is how to improve the speed of map generation and simplify the mapping process. The second problem is how to quickly arrange the style of the maps in a suitable manner, including the use of decoration and the layout of map elements. The final problem is the generation and representation of thematic features.

There are two kinds of methods used in thematic mapping: one is to use computer graphics and image processing software to directly plot thematic maps, such as photoshop, CorelDRAW, or Illustrator [40]. The advantages of this method are the ease of editing graphics for the plotting of the emergency maps. Another method is based on a combination of maps and spatial databases. In this method, thematic features are stored in a geodatabase and the mapping process is carried out using professional GIS software. Compared with the first, this method is easily used for the realization of automatic mapping and improves the speed of mapping and spatial accuracy, rendering it the more suitable method to use in the production of earthquake emergency maps.

Using the second mapping method, we propose the use of template-matching to realize such emergency mapping. The mapping process is shown in Fig. 3. The core idea of this method includes three steps, and further descriptions are listed in Section 5.1:

(1) Preparing templates of earthquake emergency maps for different audiences before the earthquake. Within the map templates, the symbols and representation methods of the earthquake emergency thematic features have been designed with regards to the method shown in Table 2. The decoration and layout of the map elements have been stored, as in the example shown in Fig. 7A.

Table 2
Representation methods for different audiences.

Mapping category	Audience oriented	mapping content	Thematic element categories	Cartographic representation method
Maps for decision-making	Earthquake emergency decision-makers	Traffic control suggestion maps, maps of earthquake rescue road	Vector/line feature	Line symbol method
		Maps of assessment result of earthquake loss	Raster/Grid	Kilometer grid (or higher resolution)
		Distribution maps of potential secondary hazard, maps of key government objectives for preservation	Vector/point feature	Fixed point symbol method
Maps of on-site disaster information	Earthquake emergency decision-makers	Distribution map of the extremely serious disaster area	Vector/polygon feature	Area method
	Auxiliary decision-making technicians	Casualty information map and map of building loss	Vector/point or polygon feature	Fixed point symbol method, dot method or area method
		Map of lifeline engineering loss	Vector/point or polyline feature	Fixed point symbol method or line symbol method
Earthquake information maps	Earthquake emergency decision-makers	Epicenter distribution map	Vector/point feature	Fixed point symbol method
	Auxiliary decision-making technicians	Map of theoretic seismic influence field	Vector/polygon feature	Area method or quality base method
	Auxiliary decision-making technicians	Geological structures map of the disaster area	Vector/polyline feature	Line symbol method
		Tremor map	Vector/polygon feature	Quality base method or area method
Physical geography and socio-economic maps	Earthquake emergency decision-makers	Map of administrative regions in disaster areas	Vector/polygon feature	Quality base method
	Auxiliary decision-making technicians	Ethnic distribution map	Vector/polygon feature	Line symbol method
		Distribution map of the important river system	Vector/polyline feature	line symbol method
		Population distribution map and GDP distribution map	Raster/Grid	Kilometer grid (or higher resolution)
	Auxiliary decision-making technicians	Digital elevation model (DEM)	Raster/Grid	Grid
		Historical earthquake map	Vector/point feature	Fixed point symbol method
		Building a distribution map	Raster/Grid	Kilometer grid
Maps of search and rescue objective	Emergency rescue workers	Location map of buried population	Raster/Grid	Kilometer grid
Maps of search and rescue support		Distribution maps of airport, docks, station	Vector/point feature	Fixed point symbol method
		Traffic map	Vector/polyline feature	Line symbol method
Maps of on-site rescue command		Location map of various levels of rescue command headquarters	Vector/polyline feature	Fixed point symbol method
		Rescue situation map	Vector/polyline feature	Flowline symbol method

Fig. 2. Representation method of earthquake information for the public (adapted from http://www.cea.gov.cn/publish/dizhenj/468/553/101420/101437/index.html).

(2) Designing the data structure of the thematic features and storing the result in the geodatabase. As shown in Fig. 7, the data structure of the seismic influence field and the corresponding data table have been designed and stored in the geodatabase. The thematic features are the core of earthquake emergency maps. There are three methods to generate thematic features: the first uses on-site information i.e. the location of the epicenter, the magnitude of an earthquake, and the focal depth. In the second method, the thematic features are provided by professionally developed models. This method is suited to thematic features that are related to earthquake and disaster information. The third method is from GIS spatial operation models, which is suited to the provision of the background features about an earthquake and the associated disaster area. For example, dams within the disaster area are "clipped" from a map of the regional distribution of dams in an affected area. The first is the easiest means of producing thematic features, but on-site information is often difficult to collect. The second method is complex as sometimes

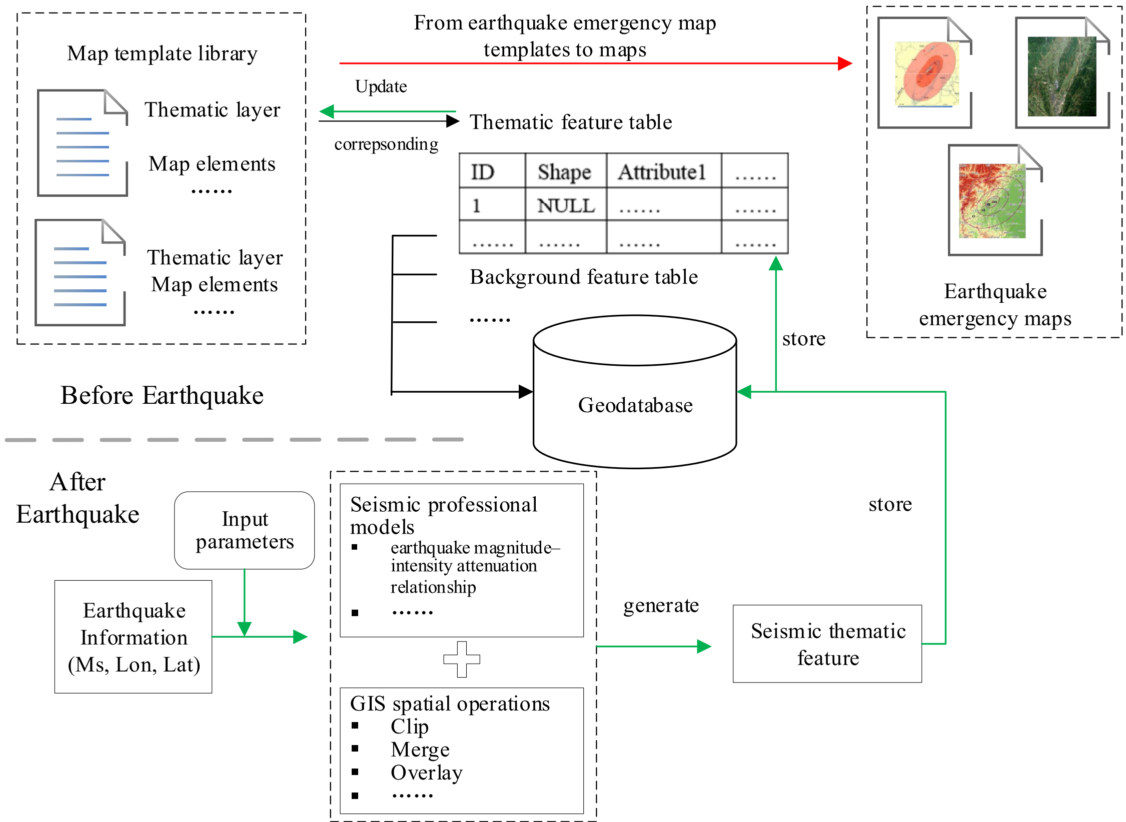

Fig. 3. Earthquake emergency mapping process base on the template-matching method. The goal of the process is to produce maps from templates as marked with the red line. Before an earthquake occurs, the map templates and geodatabase are prepared as marked with black lines. After an earthquake, the thematic features will be generated, and the corresponding geodatabase will be updated; mapping is then realized as marked in green lines.

the production of professional models requires the use of the GIS method. However, the three methods can be mixed to meet different needs. Before the occurrence of an earthquake, the parameters of the professional thematic features are unknown, and the related features will be blank and not displayed. As shown in Fig. 3, the value of the "Shape" field in this instance is "NULL".

(3) After an earthquake, the thematic features of the earthquake emergency will be generated from earthquake parameters/information (directly from on-site information or from calculations via the use of professional models). The generated professional features will be stored in the geodatabase tables. So the corresponding thematic layer in the template maps will then be

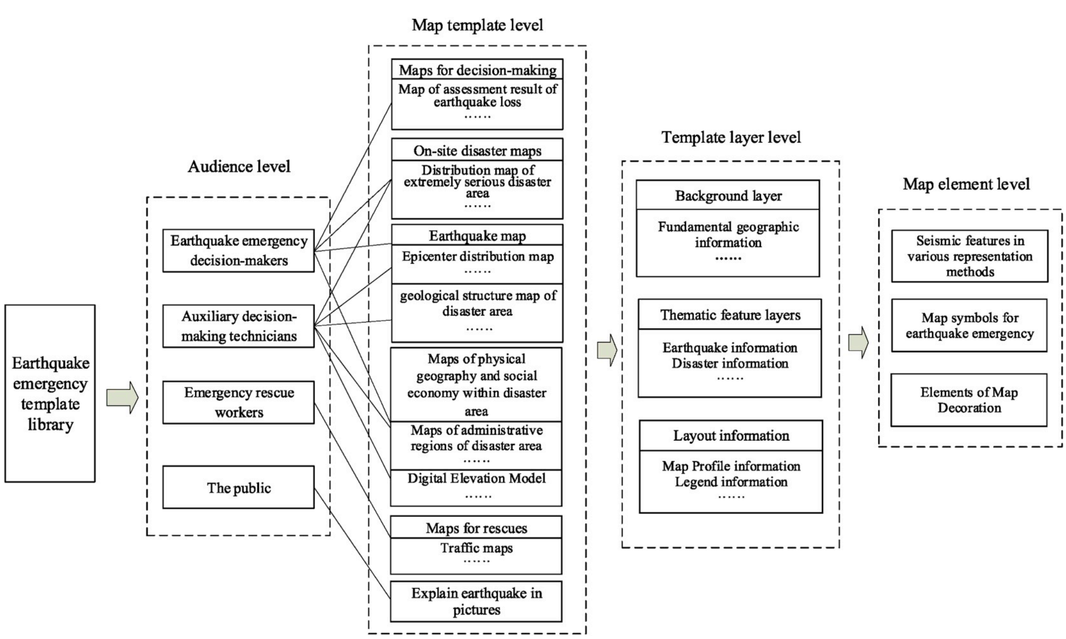

Fig. 4. The architecture of the template library.

automatically updated according to post-earthquake information in pre-arranged type, which allows the rapid production of the required map.

4.2. Template library of earthquake emergency maps

Map templates are the foundation and key to the template-matching method. We designed a template library for emergency mapping with regard to different audiences. As shown in Fig. 4, the template library consists of four levels: the audience level, map template level, template layer level, and map elements level.

(1) Audience level. We classified the templates into four types, and then build the connection/index from these different types to the detailed map templates at the template level. The different audience types also affect the collection of detailed map templates. The relationship between audience level to map templates level is, therefore, one to many relationships (1:n). This connection can help to quickly find the required map templates from an audience perspective.
(2) Map template level. The detailed earthquake emergency map templates are included at this level. From the analysis of the required content by different audiences, this level presents these requirements and thereby produces detailed map templates. The map templates level includes different kinds of map templates including the map templates for decision-making, the templates for on-site earthquake information maps, the templates for social and economic maps, and the templates for rescue maps.
(3) Template layer level. Each map template is composed of 1:n layers. There are two types of layers, one is the background layer and the other is the thematic feature layer. The background layer is sourced from fundamental geographic information including administration regions, rivers, roads, residential areas, and boundaries. The thematic feature layer represents earthquake emergency information provided by the method list in Table 2 such as the earthquake information layer or the seismic influence field layer.
(4) Elements level. Each layer consists of various map elements including representative symbols and elements of map decoration such as compass points or legends. This layer is generated through the assembly of different map elements.

5. Case study and discussion

5.1. Plotting seismic influence field map

An example of mapping a theoretical seismic influence field is presented in this section. The map of the seismic influence field is also known as an isoseismal map. Two parameters can be used to describe the scale of an earthquake: the earthquake magnitude and seismic intensity. The magnitude measures the energy released from an earthquake where higher magnitude earthquakes release more energy. However, an earthquake of high magnitude does not necessarily mean heavy losses, if there is no infrastructure within the area influenced by the earthquake. Alternatively, seismic intensity can be used to depict the damage caused by an earthquake, which refers to the degree of impact and damage caused by an earthquake. After the occurrence of an earthquake, audiences will need to know the seismic influence field quickly to estimate possible losses caused by the earthquake.

However, the actual seismic influence field is generally produced from the investigation in the field several days to months after an emergency period. The theoretic seismic intensity influence field is therefore used as an alternative for decision-making, which serves all kinds of audiences to understand the theoretical scope of earthquake damage. Producing such a map will allow an estimation of the possible losses and provide suggestions for the decision-making technicians.

Information concerning an earthquake, such as the magnitude, epicenter, and focal depth can be acquired within 15 min after the occurrence of an earthquake from the National Earthquake Monitoring Network run by the China Earthquake Administration (CEA), or from a similar network run by the U.S. Geological Survey (USGS). The theoretical field of seismic influence can then be deduced from this information using the earthquake magnitude–intensity attenuation relationship.

In China, the seismic intensity is divided into 12 grades (I ~ XII). A higher intensity value means that the impact of an earthquake is stronger. An earthquake with a seismic intensity of less than six (VI) has no particular destructive influence. The theoretical seismic influence map also consists of background layers and a thematic layer. The thematic features that correspond to the thematic layer are represented by polygons of the seismic influence field.

(1) Calculate shapes to represent the seismic influence field

The thematic features in a theoretic isoseismal map are generated from the professional model– earthquake magnitude–intensity attenuation relationship. An elliptical attenuation model is selected, which is a good approximation for earthquakes with a certain damage level. To describe this selection Equation (1) is used [49]:

$$\begin{cases} I = C_{1\alpha} + C_{2\alpha}M - C_{3\alpha}ln(R_\alpha + R_{0\alpha}) \\ I = C_{1\beta} + C_{2\beta}M - C_{3\beta}ln(R_\beta + R_{0\beta}) \end{cases} \tag{1}$$

where I is the average intensity around the long axis and short axis of the ellipse; R_α and R_β are the radius of the long and short axes; $R_{0\alpha}$ and $R_{0\beta}$ are the long and short axis saturation factors; M is the earthquake magnitude; $C_{1\alpha}$ $C_{2\alpha}$, and $C_{3\alpha}$ are regression constants of the long axis direction; $C_{1\beta}$ $C_{2\beta}$, and $C_{3\beta}$ are short axis regression constants. The regression constants are obtained iteratively according to the seismic parameters and cases of the historical earthquake.

Taking the western region of China as an example, and combining with the data given in the "Zoning Map of Seismic Parameters in China", we concretize Equation (1) and produce Equation (2):

$$\begin{cases} I = 5.253 + 1.398M - 4.164lg(R_\alpha + 26) \\ I = 2.019 + 1.398M - 2.943lg(R_\beta + 8) \end{cases} \tag{2}$$

Taking the Ms 7.1 Yushu earthquake that occurred in Qinghai Province, China on April 4, 2010, as an example, the seismic intensity ranges from VI to IX. From Equation (2), as M (7.1) and I(6) are known, then the radius of the long and short axes (R_α, R_β) can be calculated. The radii R_α, R_β should be greater than zero and thereby control the maximal value of the I (in this example is 9, noted as "IX").

(2) Generated features of the seismic influence field

Following Equation (2), the workflow for generating the features of a seismic influence field is shown in Fig. 5. Supplementary explanations for the topological operations "clip" and "merge" are provided for use in the generation of seismic influence VI and VII (for convenience VII is set as the maximum seismic intensity). Firstly, pseudo – features of influence VI and influence VII are generated. The clip operation is then used to adjust the influence of VI and to merge the fields, thereby generating the actual features of the seismic influence of VI and VII, as shown in Fig. 6.

(3) Plotting the map of the seismic influence field

ArcGIS software was used to produce a map of the seismic influence field. The basic principles used in making such a map is described in Section 4.1, an extension of this explanation is herein provided. The map includes two layers, the background layer, and the thematic feature layer. Each layer is connected to the data in the geodatabase. Before the

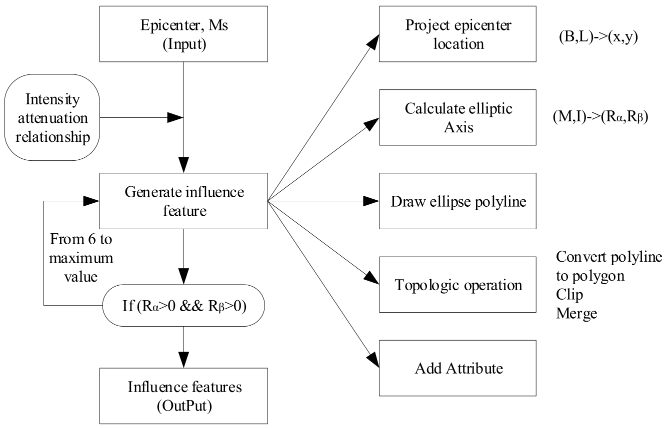

Fig. 5. Workflow to generate seismic influence field features.

occurrence of an earthquake, the "SHAPE" field in the table that corresponds to the seismic influence field layer is NULL, and the layer is invisible as shown in Fig. 7A. Fig. 7A also includes the background layer, layout information, and symbols. After an earthquake, the features pertaining to seismic influence will be generated and stored in the geodatabase as shown in Fig. 7B. At this time the "SHAPE" field of the table will be occupied and the influence feature layer will be refreshed and displayed.

The earthquake emergency mapping system is then developed, using ArcEngine 10.2 and Visual Studio C# 2012. The main interface for the system is shown in Fig. 8. In this system, both an isoseismal map and other earthquake emergency maps for different audiences are produced.

5.2. Discussion

In this study, the participants in earthquake emergency response and rescue have been classified into four categories regarding audience theory to answer two questions "who are the users of the earthquake emergency maps" and "what contents do they need". It puts the foundation for the production of emergency maps and can benefit other aspects of earthquake emergency response and rescue, such as aiding in the optimization of earthquake emergency plans and the development of emergency response information systems.

A template-matching method is then employed to realize the maps, which aim at plotting maps quickly and efficiently. The method can be realized via computing, as shown in the example. The process greatly improves the speed of making maps and is well suited to the production of emergency maps. Since the templates store the representation method for background and thematic features, the template-matching method does not need much manual operation. It is therefore suited to users who may not be proficient in map-making.

A library of the map templates is designed to manage the templates, which encompasses audience level, map template level, template layer level, and an element level. The architecture of the four levels works together to build the library. The four-level architecture is extensible and flexible. Information concerning the map style is saved in the map template level, which supports the layout of the different layers and map elements. It is therefore convenient for plotting earthquake emergency

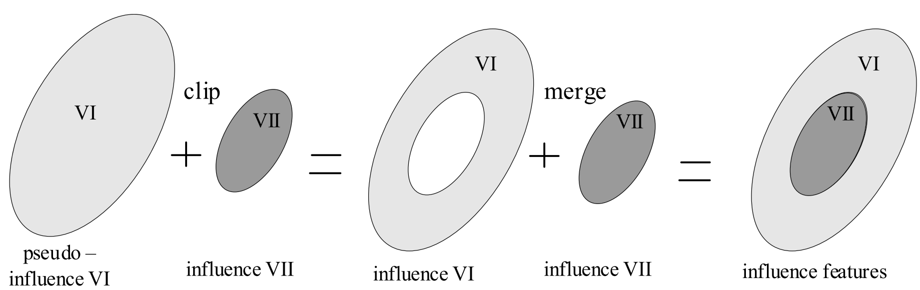

Fig. 6. Generation of seismic influence VI and VII.

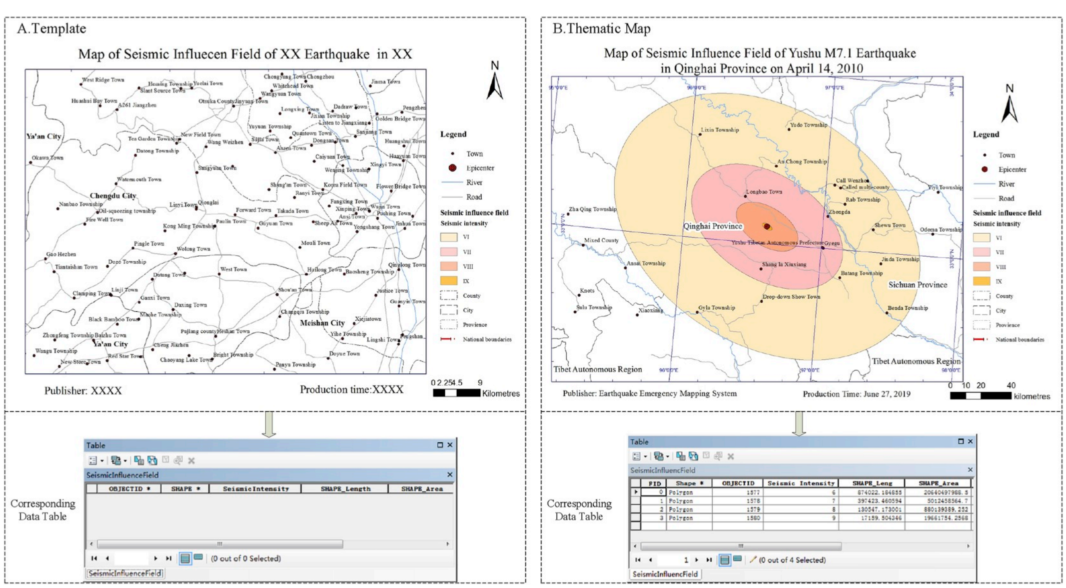

Fig. 7. Case study on the generation of the seismic influence field map of the Yushu earthquake. Fig. 8A. Before the earthquake the feature of the seismic influence field is empty; Fig. 8B. After the earthquake, the feature of the seismic influence field is updated.

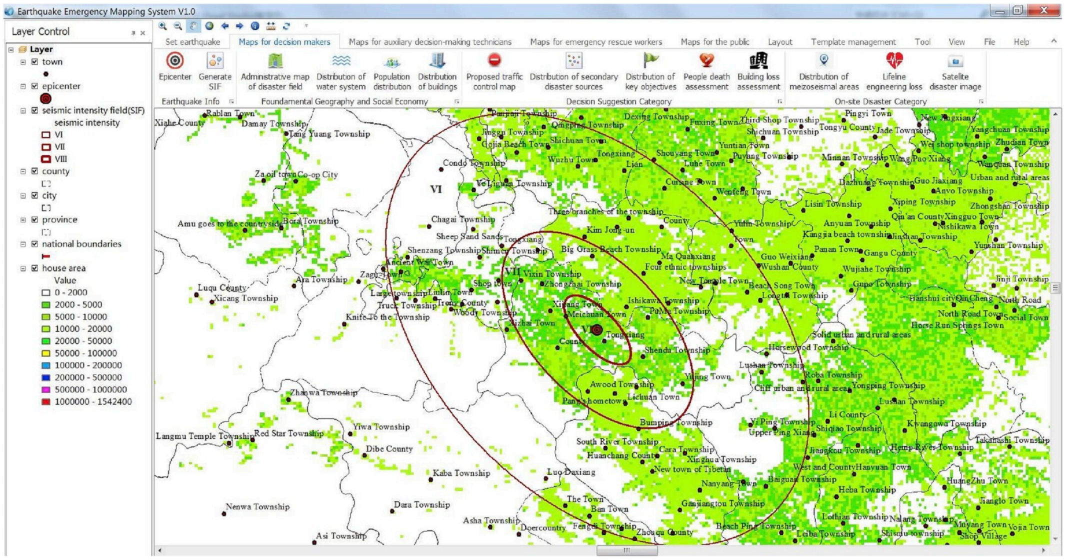

Fig. 8. The main interface of the earthquake emergency mapping system.

maps.

Although methods utilizing audience theory and template-matching are useful for the production of earthquake emergency maps, some challenges should be noted. The template-matching method has a significant impact on the artistry of the maps. The prepared map template can accelerate the speed of making maps but may lose artistry and personality. Some audiences may have specific demands such as mapping a special object (i.e. a chemical plant) or area. In such cases, special map layout (i.e. coordinate graticule), map elements (i.e. symbols) are required however they may be not included in the templates. Meanwhile, since the templates are pre-prepared and consist of many levels, they are inclined to lose flexibility. In order to cover situations of earthquake disaster as many as possible, the system has to maintain a large template library, which will increase the mapping work.

Seismic models employed to generate seismic features for updating map templates are an important part of the template-matching method. However, uncertainty is widely existing in seismic models. Currently, we do not explicitly present uncertainty in the mapping method. The uncertainty is a tricky issue in earthquake fields and many seismic models even do not provide formulas or algorithms to measure the uncertainty. Alternatively, some organizations may release multiple version emergency maps on one theme to fix it. For example, the USGS releases different versions of shaking maps in a different period after an earthquake. The CEA also releases the shaking map every hour to several hours within the period of one day after an earthquake. The values of shaking map (i.e PGA, Peak Ground Acceleration) are dynamically adjusted. In the first period, three seismic parameters of an earthquake (i.e. earthquake magnitude, earthquake location, and occurred time) will be quickly acquired through the Chinese earthquake observation network, which is composed of thousands of digital seismographs and running by China Earthquake Network Center (CENC). Then the seismic intensity is deduced through the seismic model from observed PGA values. The seismic intensity may be inaccurate since the collected PGA information is limited within this period. Meanwhile, the rupture direction is still unknown. As time goes by, more and more seismic information is observed and transmitted to the CENC. Then the information can be used to dynamically adjust the seismic intensity that PGA serves to update seismic intensity values and aftershock information is used to fix rupture direction. With such iteration and adjustment, different versions of shaking maps are released and inaccuracy is eliminated.

Merging seismic models with GIS spatial operations are crucial to the template-mapping method. However, some seismic models are complex and difficult to realize with GIS spatial operations, such as estimation models of building damage, estimation models of infrastructure damage. The difficulties may hinder map production and need further investigation.

Secondary disasters associated with the earthquake are important phenomena in the earthquake disaster emergency response and rescue. Sometime the secondary disasters may cause more serious damage than the original earthquake, for example, the 1995 earthquake of Hanshin-Awaji-daishinsai, the 2011 earthquake of the Pacific coast of Tōhoku and the 2014 Ludian earthquake. Mapping secondary disasters after an earthquake are very helpful to disaster mitigation. However, it is a tricky and complex issue with difficulties as to how to obtain and how to represent secondary disaster information.

As the foundation of the mapping, the secondary disaster information can be obtained in two ways. One way is collecting secondary disaster information from satellite imagery [32,50]. The satellite imageries provide a situational overview of the extent and scale of the secondary disasters, and then improve the speed and effectiveness of mapping [51]. A major challenge of the satellite image method is a time delay in images collection from several hours to several days or even facing cloud cover problems sometimes [14,51]. Meanwhile, map templates in this study do not directly suit satellite imageries without corresponding levels and need to be extended in the future.

Another way is deducing secondary disaster information from theoretic models. So various models are required to different kinds of secondary disasters, such as the debris flow hazards model [52] and the landslide susceptibility model [53]. For emergency response, real-time or near-real-time models with high calculation speed are essential to effective mapping [53]. The information about an earthquake is scarce within the co-earthquake period. How to guarantee the accuracy of the models with limited known parameters is a big challenge of this method.

6. Conclusions

The production of thematic maps after the occurrence of an earthquake is an effective means of presenting information concerning earthquakes and the associated disasters, which plays an important role in improving the effectiveness of earthquake emergency response and rescue. However, the effective production of emergency maps with regards to the requirements of different participants is a challenge. We focus on two important questions in making earthquake emergency maps: (1) Who are the maps for and what content do they need? (2) How can maps be effectively produced?

In this paper, we have adopted audience theory to analyze the identity of the users of earthquake emergency maps and have classified them into four categories: earthquake emergency decision-makers, auxiliary decision-making technicians, emergency rescue workers, and the public. The contents of the earthquake emergency maps for the different audiences are then studied, in forms including decision-making suggestion maps, disaster information maps, earthquake information maps, natural and social economy maps, search and rescue objective maps, and supporting maps for search and rescue. We therefore answer the first question.

We then present methods for representation within the earthquake emergency maps with regards to different map contents. A template-matching method is proposed for making earthquake emergency maps. This process includes two key steps: prior to an earthquake map templates are prepared for different audiences and the corresponding geodatabase is designed. After the occurrence of an earthquake, seismic thematic features are generated from professionally developed models and are updated in the geodatabase. Since the templates store the map styles according to the representation methods, updates to the thematic features will be appropriately displayed. The library of map templates is designed and a case study presented.

We conclude that the division of the users of earthquake emergency maps based on audience theory is useful. Doing so creates a foundation from which the contents of earthquake emergency maps can be understood. The template-matching mapping method and related template library can therefore accelerate the speed of mapping. This method for mapping is not only suitable for use in the creation of earthquake emergency maps but is also useful for the production of emergency maps for other disasters. The method is also of benefit to individuals without professional knowledge of using GIS for the production of thematic maps. In the future, we will further study the methods that combine seismic models with GIS spatial operations and extend the audience mapping system by adding versatile functions such as mapping secondary disasters and merging satellite imageries.

Declaration of competing interest

The authors declared that they have no conflicts of interest to this work.

We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

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Appendix A. Supplementary data

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