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Perspectives for flood risk assessment and management for mega-city metro system

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ABSTRACT

This paper presents an overview on the risk assessment approaches for inundation of metro systems based on regional flood risk assessment methods. Detailed summarization is conducted based on four types of regional flood risk assessment methods, including (i) statistical methods, (ii) multi-criteria analysis, (iii) analysis using geographical information system (GIS) and/or remote sensing (RS), and (iv) scenario-based analysis. After reviewing of the existing methods in literatures, a perspective approach of evaluating inundation risk for metro systems is proposed. The proposed approach has the following two characteristics: (i) from regional to local, and (ii) from qualification to quantification. The Guangzhou Metro System is used to demonstrate the application of the perspective methods for flood risk assessment of metro system. The risk prevention procedure uses an iterative cycle that includes risk assessment, precaution, prediction, and technical countermeasures. The integration of GIS, global position system (GPS) and build information modelling (BIM) for development of early warning and risk management systems is recommended to manage the risks of inundation of metro system.

1. Introduction

The total world population has reached more than 7 billion in 2018 (Gutierrez et al., 2014; UNFPA, 2018). This large population has resulted in rapid urban expansion with consequent impacts on the environment. To address environmental issues, people need to learn how to survive in a varying environment and to create community resilience to natural disasters (Djalante, 2012; Du et al., 2014a,b; Udomchai et al., 2018). Flooding is one of the most hazardous natural disasters, and is frequently responsible for loss of life and severe damage to infrastructures and the environment (Hapuarachchi et al., 2011). Natural disasters cause devastating consequences including loss of life and huge socioeconomic loss worldwide, where 34% of the natural disasters are directly related to floods leading to 1254 deaths and more than 2.5 billion dollars of socioeconomic loss per annum from 1960 to 2017 (Petit-Boix et al., 2017). The urban areas accommodate about 53% of the population in this world (Petit-Boix et al., 2017), and this value is expected to increase to 70% by 2020 (UN, 2012). Nevertheless, the urban areas with large populations are much more vulnerable to flooding disasters (Jha et al., 2011; Lyu et al., 2018a,b).

With the increase of urban waterlogging caused by flooding, many urban water management policies were proposed for the urban drainage system (Deng et al., 2013; Emanuelsson et al., 2014; Mugume et al., 2015; Campisano et al., 2017; Shao et al., 2017; Xu et al., 2018). Yang et al. (2011) explored an optimized algorithm to select sustainable flood retention basin (SFRB), which provided a rapid scientific tool for SFRB assessment in practice. Mugume et al. (2015) proposed a new analytical approach based on global resilience analysis to assess the performance of urban drainage systems.

Although great achievements have been obtained from these existing researches, destructive flood events in mega-cities still happen. In addition, floods not only cause catastrophic submerging of surfaces but also severe inundation of underground facilities (Quan et al., 2011; Lyu et al., 2016, 2018a; Wu et al., 2016, 2018). Therefore, there is an urgent need for proper storm-water management practices in urban regions to reduce the damage caused by flood disasters. This paper reviews the methods for flood risk assessment and proposes possible approaches to assess the inundation risk for underground facilities. The perspective approaches include two aspects: (a) from regional to local, and (b) from qualification to quantification. The objectives of this paper are to (*i*) provide a review of current research on regional flood risk assessment methods; (*ii*) propose perspective methods for flood risk assessment of

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metro systems; and (*iii*) propose perspectives for risk assessment, precaution, prediction, and technical countermeasures for inundation prevention to keep sustainability of the total environment for megacities.

2. Flood risk to urban metro system

A large number of urban facilities (e.g., underground metro systems, shopping malls, utility channels, and parks) have been constructed to accommodate the rapid urbanization (Shen et al., 2009, 2010, 2014; Tan et al., 2016, 2017; Kim et al., 2017; Tan and Lu, 2018). Underground constructions make full use of underground space to accelerate economic development; however, these underground constructions also cause environmental and geological problems associated with long-term land subsidence (Galloway and Burbey, 2011; Shen and Xu, 2011; Xu et al., 2014, 2017). Due to disturbances caused by underground construction, the environment becomes vulnerable to natural disasters, e.g., floods, storm surges, tsunamis, typhoons, and tornados (Lyu et al., 2016, 2017). During the past two decades, flood disasters have resulted in enormous deaths, injuries, economic losses, and even the loss of function in many cities (Chen et al., 2013; Lyu et al., 2018c,d,e). Extreme flood events have caused catastrophic damage to both ground buildings and underground infrastructure e.g., metro tunnels and stations. Floodwater may also cause contamination in the underground space, which degrades its commercial value (Shen et al., 2015a,b, 2016, 2017; Zhao et al., 2016; Qiao et al., 2017; Wu et al., 2017a,b; Peng and Peng, 2018).

Table 1 lists the published incidents of flood events in metro systems. In 2016, China suffered from extreme rainfall events that caused many floods to underground infrastructure to Guangzhou and Wuhan. Fig. 1 shows the flooded metro stations during heavy rainfall in Guangzhou and Wuhan. Changpan Station of metro line 6 in Guangzhou was inundated on 10th May and Wuhan Station was flooded on 6th July (Lyu et al., 2016). These incidents demonstrate an urgent need for research to prevent flood risk and minimize the damage of catastrophic events in underground space.

Although there is an urgent need to understand the inundation risk for underground infrastructure and a few studies done in literature (Suarez et al., 2005), there is still a gap between the demands in practice and the methods for assessing this risk. For example, the current researches have mainly concentrated in the risk for regional flood disaster (Cunnane, 1988; Parida et al., 1998; Scawthorn et al., 2006). There is a urgent demand to generate prospective approaches for inundation risk in underground infrastructure based on the existing methods for regional risk assessment.

To avoid the confusion, we present here the terminologies with related references used in this review work. According to Rovins et al. (2015), risk is the combination of the hazard, exposure, and vulnerability. Specifically, a hazard is an agent, which can induce harm or damage to humans, property or environment. Exposure refers the presence of the disaster body at risk (e.g. buildings, infrastructure, environments) that could be negatively affected while vulnerability characterized the different disaster body at risk towards a given hazard intensity (Ghesquiere et al., 2012; Rovins et al., 2015). A hazard poses no risk if there is no exposure disaster body. Moreover, the flood risk refers to a potential disaster related to flood involving losses in lives, health status, livelihoods, assets, and services (Gallina et al., 2016). Whereas, the inundation risk refers to a potential disaster associated with underground infrastructure. Inundation risk refers to the risk in local area, while the flood risk represents the risks in regional area (Quan, 2012; Lyu et al., 2018a).

The traditional conceptual framework for consideration of urban flood risk involves the comprehensive interaction between hazard, exposure, and vulnerability. In the global context of the rapid urbanization and climate change, the flood risk shows some new features (Xu et al., 2018). Fig. 2 shows the conceptual framework for urban flood risk. As shown in Fig. 2, climate change results in an increase in hazard intensity and frequency. Rapid urbanization, including population expansion and urban infrastructure construction, aggravates the exposure and vulnerability of infrastructure (Quan, 2014). The joint effects of climatic change and urban expansion indicate that flood risk will very probably be aggravated in many regions (Muis et al., 2015). Therefore, development of flood risk assessment methods and management strategies are urgently necessary, especially for underground infrastructure.

3. Overview of flood risk assessment method

3.1. Regional flood risk assessment

Table 2 summarizes the representative researches on flood risk assessment methods from 2000 to 2017. Based on these studies, there are four approaches to assess flood risk: (1) statistical methods, (2) multi-criteria analysis, (3) analysis based on Geographical Information System (GIS) and Remote Sensing (RS) techniques, and (4) scenario-based inundation analysis. Statistical methods are based on historical records to assess flood risk (Black and Burns, 2002; Werritty, 2002; Nott, 2006; Jin et al, 2018a,b). Multi-criteria analysis is a qualitative assessment method that uses an index system to assess risk (Steuer and Na, 2003; Hajkowicz and Collins, 2007; Su and Tung, 2014; Xiao et al., 2017). GIS-based techniques combined with RS provide technical supports for flood risk assessment (Schumann et al., 2000; Islam and Sado, 2002; Chen et al., 2009; Elkhrachy, 2015; Kabenge et al., 2017). Scenario-based inundation analysis is a quantitative method that utilizes scenario analysis to predict flood risk immediately before an occurrence (Horritt and Bates, 2002; Karamouz et al., 2010; Chang et al., 2015; Yin et al., 2016; Pant et al., 2017). These four methods will be discussed in detail in the following sections.

3.1.1. Statistical methods

The statistical methods require long-term historical records, which assumed that "the past is the key to the future", that is, "historical floods can be used to predict future ones" (Nott, 2006). This method is characterized by simple calculations that divided flood risk assessment into a hazard assessment and a vulnerability assessment. Black and Burns (2002) presented the changes in flood risk with time for Scottish Rivers by re-assessing flood records. Werritty (2002) applied trend analysis and current climate change scenarios to identify the problems of water resources. Nott (2006) proposed that long-term historical flood

Table 1
Historical inundated cases of metro systems.

Incident date	Location	Damage	Reference
10 May 2016	Guangzhou, China	Eight deaths, one metro line flooded	Lyu et al., 2016, 2018a
22–29 October 2012	New York, United States	Seven metro tunnels and three vehicular tunnels flooded	Blake et al., 2013
6 September 2003	Virginia, United States	Flooded the tunnel system in just 40 min with almost 167 million litres	Sosa et al., 2014
August 2002	Prague	About one third of the length of the Prague Metro were inundated	Jakoubek, 2007
29 June 1999	Fukuoka, Japan	Metro and underground space inundated.	Herath and Dutta, 2004
13 April 1992	Chicago	Floodwater seeped past bulkheads into adjacent metro tunnels, closing down the entire metro system.	Inouye and Jacobazzi, 1992

Fig. 1. Metro station inundated during heavy rainfall: (a) Changpan Station flooded on May 10th, 2016 in Guangzhou, Guangdong Province (Lyu et al, 2016); (b) Wuhan Station flooded on July 6th, 2016 in Wuhan, Hubei Province (Lyu et al., 2018a,b).

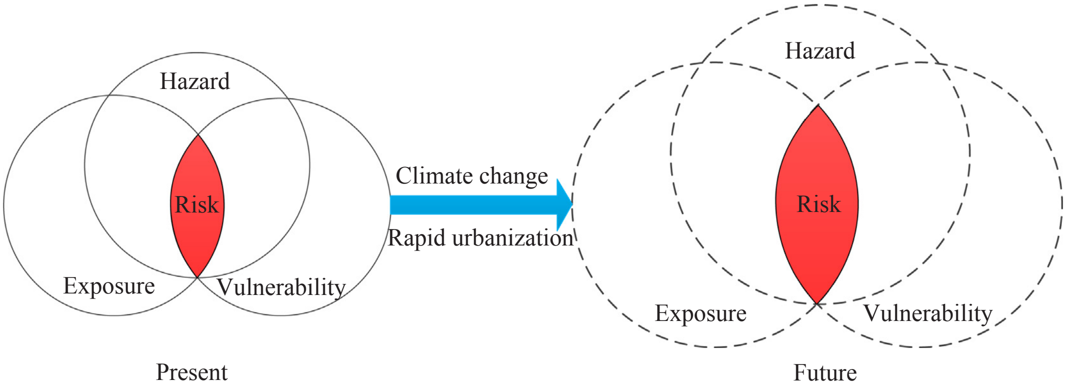

Fig. 2. Conceptual framework of urban flood risk.

records are one of the most useful references for flood risk assessment. Although the assessment results can present the risk for an investigated area, this type of methods requires a huge amount of data and may suffer from the accuracy problem in evaluating the spatial distribution of floods.

3.1.2. Multi-criteria analysis

Multi-Criteria Analysis (MCA) provides a way to analyse complex decision-making problem that was firstly proposed by Voogd (1983). Many methods have been proposed to investigate MCA since 1960s (Hajkowicz and Collins, 2007; Zhu et al., 2016a). The new MCA method is always combined with Fuzzy Analytic Hierarchy Process (FAHP) and GIS techniques to enhance the approach (Fu, 2008; Fernández and Lutz, 2010; Wang et al., 2011; Zhu et al., 2016a). Steuer and Na (2003) identified 265 MCA studies which they classified in terms of methodological approaches. Su and Tung (2014) also conducted detailed research on the application of MCA to estimate flood-induced vulnerability of city. Xiao et al. (2017) used MCA combined with GIS to analyse the effects of different risk attitudes of the decision makers on the assessment result. Fig. 3 shows a conceptual framework of MCA for flood risk. In this procedure, flood risk is the object layer; the index layer includes hazard, exposure, and vulnerability; and the sub-index layer includes the factors that influence flood risk (e.g., rainfall, topography, drainage system, and land use). However, MCA has limitations in the determination of subjective factors, since this method mainly depends on experts' judgments to make decisions.

3.1.3. GIS and RS techniques

Mejia-Navarro et al. (1994) initially attempted to use GIS for flood hazard assessment. Correia et al. (1999) considered GIS is a useful tool to integrate data from different sources, which can provide a flood risk map under different scenarios of urban growth. Schumann et al. (2000) developed a GIS-based method for a rainfall-runoff model. Liu et al. (2003) estimated the spatial distribution of runoff by incorporating several parameters (such as slope, land use, and soil type) into a rainfall-runoff model. Islam and Sado (2000, 2002) proposed countermeasures in a flood disaster map by combing RS technology and GIS. Chen et al. (2009) applied a GIS-based model, which included a storm runoff model and an inundation model to analyse inundation risk in an urban university campus. Elkhrachy (2015) used satellite images and GIS tools to generate a flash flood map for Najran, Saudi Arabia. Kabenge et al. (2017) applied the RS and GIS techniques to draw flood hazard maps for the Nyamwamba watershed in Western Uganda, which helps local government to customize land use plans and to coordinate emergency response. These studies provide solid technical supports for flood risk assessment and management.

Fig. 4 shows the conceptual framework for flood risk assessment combined with GIS and RS techniques. Flood risk is considered as the interaction between the environment, the bearing body, and the hazard. The GIS-based flood risk model consists of an input layer and output layer. The RS technology is used to obtain a Digital Elevation Model (DEM) and a Digital Surface Model (DSM) to reflect the characteristics of urban topography. The urban rainstorm model usually includes a Strom Water Management Model (SWMM) (Hsu et al., 2000; Jiang et al., 2015), Soil Conservation Service (SCS) model (Huang et al.,

Table 2
Summary of representative researches on flood risk assessment methods (from 2000 to 2017).

Classification	References	Methodologies	Key objectives	Major findings/contributions
Statistical methods	Black and Burns (2002)	Historical flood records	Assess flood risk in Scotland	Proposed a new statistical methodology based on the largest flood and catchment databases
	Werritty (2002)	• Trend analysis • Current climate change scenarios	Examine recent trends in precipitation and runoff across Scotland	• Identified the issues for water resources • Helped managers faced with environmental uncertainty
	Nott (2006)	Long-term historical records	Provide useful resources for risk assessment	Helped urban planners understand the long-term records of natural hazards
Multi-criteria analysis	Steuer and Na (2003)	Categorization and statistics	Provide an overview of multiple criteria decision making (MCDM)	Explored the application of multi-criteria technologies
	Hajkowicz and Collins (2007)	• Fuzzy set analysis • Pairwise comparison • Outranking	Water policy evaluationStrategic planningInfrastructure selection	Provided an understanding of the development and current status of multiple criteria analysis (MCA)
	Su and Tung (2014)	• Excepted opportunity loss (EOL) • Preference ranking organization method of enrichment evaluation	Decision problems involving multiple criteria	Demonstrated uncertainty in decision making
	Xiao et al. (2017)	• MCA • GIS • Spatial ordered weighted averaging	Propose an adaptable method for flood risk assessment	Developed an integrated flood hazard assessment framework
GIS and RS techniques	Schumann et al. (2000)	Three semi-distributed modules	Use statistical descriptions of catchment characteristics to consider spatial heterogeneity	Solved the problem of parameterization of physically based models
	Islam and Sado (2002)	• GIS • RS	Demonstrate the technique to develop a flood hazard map	Developed a new flood map for Bangladesh
	Chen et al. (2009)	• Storm-runoff model • Inundation model	Develop a GIS-based urban flood inundation model (GUFIM)	Determined that GUFIM has more accurate results
	Elkhrachy (2015)	• Satellite image • GIS • AHP	Obtain a flash flood map for Najran, Saudi Arabia	Formulated an efficient method to accurately delineate flood hazards in Najran, Saudi Arabia
	Kabenge et al. (2017)	• RS • GIS-based technology	Define flood risk by development of a flood hazard map	• Customized land use plans • Coordinated emergency response
Scenario-based analysis	Bates and De-Roo (2000)	LISFLOOD-FP model	Predict flood-inundation extent	Maximized the inundation prediction ability
	Horritt and Bates (2002)	• HEC-RAS model • LISFLOOD-FP model • TELEMAC-2D model	Calibrate the three models	HEC-RAS and TELEMAC-2D: provided good predictions,LISFLOOD-FP: calibration by independent inundated area data; obtained acceptable results
	Karamouz et al. (2010)	Select the best management practices (BMP)	Achieve reliable results to use in real-time urban planning	Proposed an algorithm for selecting the BMPs
	Chang et al. (2015)	• 1D sewer flow model • 2D overland flow model	Select an appropriate approach for urban flood simulation	Closer to the records than other approaches
	Yin et al. (2016)	• FloodMap HydroInundation2D • Flood depth-dependent measures	Simulate flood inundation for each scenario	Flood response was a function of spatial-temporal distribution of precipitation

2017), and the MIKE model developed by Danish Hydraulic Institute (Mignot et al., 2006). Based on the data from the input layer, GIS tools can analyse the hazard, exposure, and vulnerability in the output layer. Finally, the spatial distribution of comprehensive flood risk can be mapped using a GIS platform. There are some disadvantages to this approach: (*i*) the equipment for RS has high costs, (*ii*) the data for the input layer demand high resolution, and (*iii*) most of these methods can give accurate qualitative assessments, whereas quantitative assessments may have inaccuracies.

3.1.4. Scenario-based inundation analysis

Scenario simulation analysis can be used for the evaluation of flood risk under different scenarios with changing spatial domain (Willems, 2013). This method includes the use of geomorphology, topography, and urban drainage system data. Scenario-based inundation analysis is a quantitative method that combines various data and reflects abundant

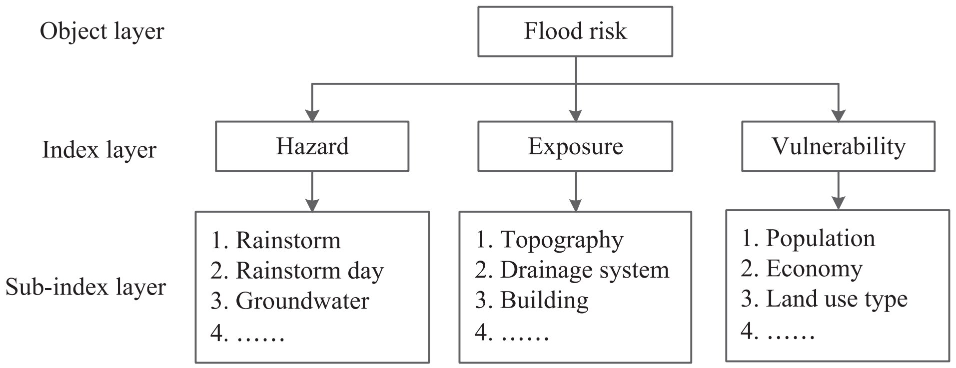

Fig. 3. Conceptual framework for the MCA method to assess flood risk.

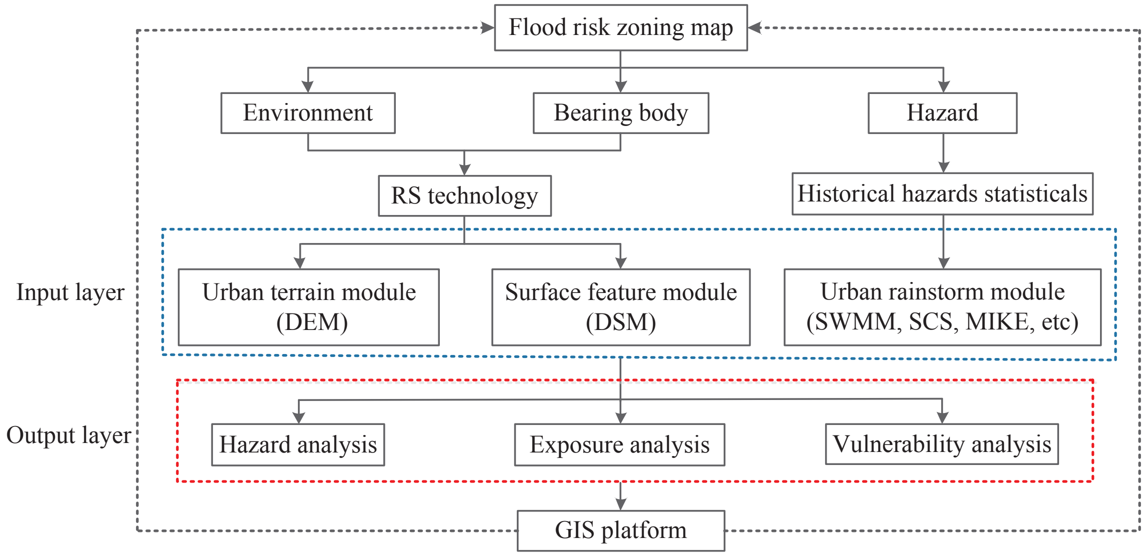

Fig. 4. Conceptual framework for flood risk assessment combined with GIS with RS techniques.

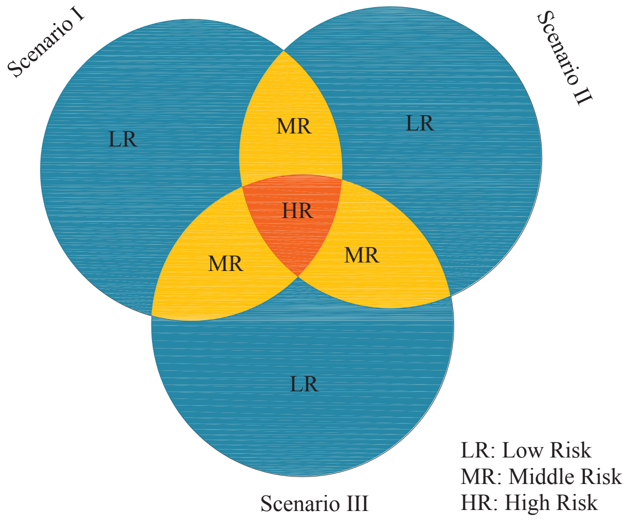

Fig. 5. Conceptual map of the effects of inundation frequency on flood risk (modified from Quan, 2012).

information on flood risk. Karamouz et al. (2010) proposed an algorithm to choose the best management practices to improve the system reliability in dealing with urban flash floods. Chang et al. (2015) proposed a new approach to simulate dynamic flow interactions between the storm sewerage system and surface runoff in urban areas. Accurate modelling of the urban inundation process became possible with the development of raster-based flood models (e.g., LISFLOOD and FloodMap) and the appearance of high resolution images from LiDAR, GIS and RS techniques (Bates and De-Roo, 2000; Horritt and Bates, 2002; Sampson et al., 2012; Yin et al., 2016). Inundation simulation under different scenarios can produce inundation maps (including flood depth and extent), which provide valuable information for appropriate risk mitigation measures. Based on the concept of inundation frequency effects, the frequency of inundation can reflect the flood risk, which is believed to be greater in areas with frequent inundation (Cunnane, 1988; Parida et al., 1998; Quan, 2012, 2014). Fig. 5 shows the conceptual map of inundation frequency effects. It is supposed that the overlapped area with inundation under scenarios I, II, and III has a High Risk (HR) of flooding; the overlapped areas with inundation under scenarios I and II, II and III, and III and I have a Middle Risk (MR); and the areas with inundation under only scenario I, II, or III have a Low Risk (LR). However, scenario-based inundation analysis is commonly used to predict inundation risk in a small region, but flood disaster usually happened in a regional scale. Therefore, the scenario-based inundation analysis should be enhanced to a regional scale.

3.2. *Risk assessment of underground infrastructure*

The existing methods for risk assessment of underground infrastructure focus on the fuzzy theory, uncertainty theory, and mathematical statistics, which combine qualitative and quantitative analyses (Yu et al., 2017). Table 3 summarizes representative research on risk assessment for underground infrastructure from 2000 to 2018. Regarding underground construction, a number of methods have been proposed for risk assessment, including Multi Criteria Decision Making (MCDM) (Linkov et al., 2006; Wang and Lee, 2009), Monte Carlo simulation (MCS) (Rezaie et al., 2007; Wu, 2008), Fault Tree (FT) method (Shahriar et al., 2008; Li et al., 2013; Hyun et al., 2015), Fuzzy Set (FS) method (Chen and Chen, 2008; Hejazi et al., 2011; Idrus et al., 2011) and, most recently, optimization methods (Lohani et al., 2011; Kashani et al., 2014; Yin et al., 2017, 2018a, 2018b). The previous researches provide theoretical supports to the inundation risk evaluation of underground infrastructure.

3.2.1. *Risk for metro tunnels*

Metro tunnels play a critical role in the public transportation system of mega-cities. Risk assessments of metro tunnels include the risks during both tunnel construction and operation (Reilly and Brown, 2004; Isaksson and Stille, 2005). During metro operation, both natural and artificial hazards (e.g., flooding disasters) pose risks for the metro system. Einstein et al. (1994) provided a pioneering research in which risk assessment was applied to analyse both long-term risk and construction risk for tunnels. Moreover, Einstein et al. (1994) assessed the comprehensive risk of the Adler tunnel under different construction schemes. Nezarat et al. (2015) applied F-AHP to analyse the geohazards risk for Golab tunnel construction (Alan, 2010; Nezarat et al., 2015). In addition, numerical simulation methods are also effective for analysing the uncertainty of underground construction (e.g., tunnel construction). Shen et al. (2014) proposed a model to predict settlement risk induced by land subsidence in the soft deposits of Shanghai. These previous researches provide both a technical consideration of tunnel behaviour and risk evaluation of inundation risk for underground infrastructure.

Table 3
Summary of representative research on risk assessment for underground infrastructure (from 2000 to 2018).

References	Methodologies	Key objectives	Major findings/contributions
Isaksson and Stille (2005)	Monte Carlo simulation	Proposed a probabilistic model for the estimation of construction cost and time for tunnelling projects.	● Obtained a sufficient basis for decision making ● Developed an estimation model that considers the impact of different geological factors
Rezaie et al. (2007)	● Monte Carlo simulation ● Rotary algorithm	● Discussed uncertainty probabilities ● Intellectualized the classic Monte Carlo simulation ● Represented a rotary algorithm	● Considered the interactions of uncertainties ● Proposed a rotary algorithm ● Avoided impossible modes in Monte Carlo simulations ● Assured right decisions in risk analysis
Shahriar et al. (2008)	Decision tree	Selected Tunnel Boring Machine (TBM) based on geotechnical risk minimization	Proposed an approach for the selection of appropriate measures to decrease risk as much as possible
Wang and Lee (2009)	● Multi criteria decision making (MCDM) ● Fuzzy TOPSIS	Proposed a new fuzzy TOPSIS by integrating subjective and objective weights	Proposed a novel approach that involves the end-user in the whole decision-making process
Nezarat et al. (2015)	● Fuzzy analytical hierarchy process (FAHP) ● Multi criteria decision making (MCDM)	● Managed and respond to the associated risks in tunnel and underground construction ● Identified risk factors	Improved use of the FAHP method by using MCDM sensitivity analysis
Yu et al. (2017)	● Probabilistic risk analysis ● Bayesian network	Proposed a probabilistic risk analysis method for diversion tunnel construction	Enabled comprehensive and effective risk analysis of tunnel construction

3.2.2. Flood risk assessment for metro tunnels

As presented in the aforementioned context, many studies have been conducted for the risk assessment of natural and artificial hazards, whereas few studies have focused on flood risk for metro tunnels. The early research on flood risk of underground infrastructure started in Japan (Herath and Dutta, 2004). Table 4 summarises several flood risk assessments for metro tunnels, in terms of methodologies, key objectives and major findings/contributions. Herath and Dutta (2004) described floods in underground facilities in Japan and presented a 3D modelling system designed for simulating urban floods, including underground facilities. Hashimoto and Park (2008) applied mathematical theory to analyse the flood event that occurred in Fukuoka City on June 29, 1999, and caused the metro station and underground space to be inundated. Based on the previous research, Aoki et al. (2016) proposed anti-inundation measures for the underground stations of the Tokyo Metro. In recent years, the frequency of flood events in metro lines call for researches on inundation risk assessment and mitigation measures for underground infrastructures (Lyu et al., 2016, 2018a,b). In addition, groundwater also threats the safety of metro tunnel through leaking (Wu et al., 2014; Maleki, 2018). Hassani et al. (2018) applied numerical simulation and Raymer solution method to predict the groundwater inflow values during metro tunnel construction. Colombo et al. (2018) turned out a 3D numerical model into a stochastic model to assess the hydrogeological hazards for the underground infrastructures caused by the rise of the groundwater level observed in Milan, Italy. This research found that flooding hazard increases with the increasing depth of the infrastructure. The existing researches can be employed as the basis of the flood risk assessment of metro tunnels.

4. Perspectives on flood risk assessment in metro systems

4.1. Approaches for flood risk evaluation and mitigation

According to the existing researches, both from regional flood risk assessment methods and risk assessment approaches for underground infrastructure, perspectives on flood risk assessment for underground metros are proposed. Fig. 6 shows the perspective for flood mitigation in underground infrastructure. The procedure includes four steps: (1) risk evaluation (e.g., AHP analysis), (2) early warning system, (3) scenario-based prediction, and (4) technical countermeasures. AHP analysis is a qualitative method, which can yield a qualitative assessment of flood risk for an underground metro. According to the qualitative

Table 4
Summary of research on flood risk assessment for metro tunnel (from 2000 to 2018).

References	Methodologies	Key objectives	Major findings/contributions
Herath and Dutta (2004)	● 3D modelling system ● 2D diffusive model	Proposed a mathematical model to predict underground inundation	Applied the model to simulate underground flooding in Fukuoka, Japan
Suarez et al. (2005)	● Urban transportation modelling system (UTMS) ● Remote sensing ● GIS technology	Developed a method to assess the effects of flooding events on the performance of urban transportation networks	Explored the relative impact of climate change on the delays caused by increased coastal and riverine flooding
Hashimoto and Park (2008)	Momentum and continuum equations	Developed a two-dimensional flood simulation model in dense urban areas	Considered the effect of the high density of buildings and houses on flood flow
Quan et al. (2011)	Scenario-based inundation analysis	Analysed and assessed the waterlogging risk of a subway in a central urban area	Provided important information for local government to improve waterlogging risk assessment
Aoki et al. (2016)	Analyse the existing inundation control measures	Mitigate flood damage in underground infrastructure	Put forward a new direction for flood control measures
Lyu et al. (2018a)	● FAHP analysis ● Qualitative analysis	Assessed flood risk of the metro system in Guangzhou City	Proposed a GIS-based modelling approach to assess flood risk in the metro system
Wang et al. (2018)	● Weighting method ● Normal cloud model	Proposed a new method for water inrush evaluation.	The proposed method demonstrates good practical reference for risk assessment of tunnel construction
Hassani et al. (2018)	● Analytical solutions ● Empirical methods ● Numerical modelling	Compared different methods used for evaluation of steady state groundwater inflow to a shallow circular cross section tunnel.	Raymer equation can provide more reliable estimation of inflow rate for shallow tunnels to other analytical and empirical solutions
Colombo et al. (2018)	● Numerical modelling ● Stochastic model	Analyzed the hydrogeological hazard.	Flooding hazard increases with the increasing depth of the infrastructures

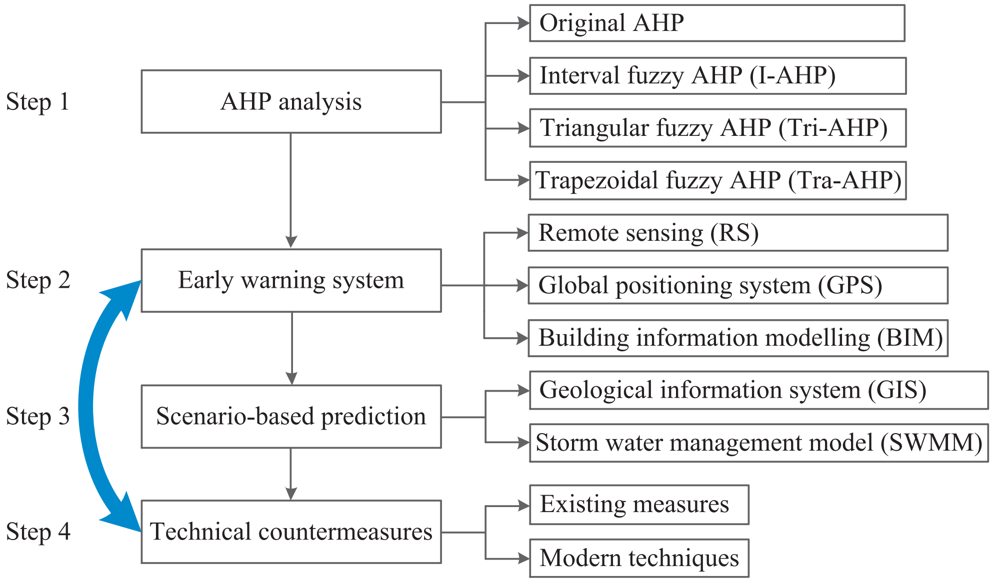

Fig. 6. Perspectives on flood risk management for metro systems.

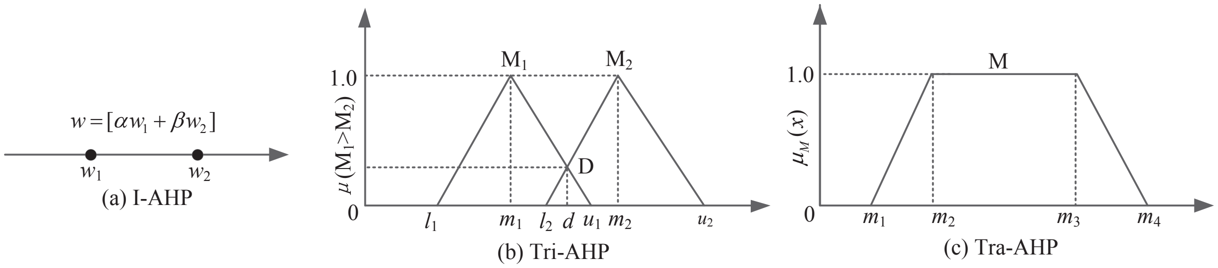

Fig. 7. Fuzzy AHP methods for flood risk assessment: (a) I-AHP, (b) Tri-AHP, and (c) Tra-AHP.

assessment, an early warning system is recommended to monitor the sections with high risk in an underground metro (Tu et al., 2018). Scenario-based inundation analysis is a quantitative method, yielding a quantitative prediction of the risk for an underground metro. Scenario-based prediction is expected to provide a more accurate assessment on the basis of qualitative assessments and early warning systems. Based on the combination of the qualitative and quantitative assessments and the early warning system, technical countermeasures are proposed to mitigate inundations in underground metros. This procedure can be summarized as an iterative circular system that combines the assessment analysis and countermeasures to mitigate inundations. The following section will provide a detailed discussion on risk assessment approaches.

4.2. Risk assessment from regional to local

The proposed perspectives on inundation risk assessment approaches for underground infrastructure (e.g., metro tunnels) include two procedures: (i) from regional to local and (ii) from qualification to quantification. It is supposed that the regional flood risk has a crucial influence on the inundation risk of any metro system. This means that a high level of flood risk within a region indicates a high level of inundation risk for metro lines in the region. This method is referred to as "from regional to local", that is from the regional flood risk level to the metro system risk level. Therefore, the reliability of the regional flood risk assessment is very important for the reliability of the metro system inundation risk. To determine the potential inundation risk of a metro system, the original AHP and fuzzy AHP are combined to assess the regional flood risk. Then, the inundation risk of the metro system is assessed by the risk level within the range of 500 m from a metro line (Lyu et al., 2018a).

AHP is a comprehensive method based on multi-critical indices that are used to perform both qualitative and quantitative analyses (Saaty, 1977, 2008). For the AHP method, Saaty (1977, 2008) defined a scale from 1 to 9 (or their reciprocals) with assigned linguistic terms to express the relative importance of pairwise comparisons. The AHP method uses a single weight for each assessment factor to express relative importance. To overcome the shortcoming of the crisp value from the original AHP, the extension to fuzzy AHP methods is conducted through calculation of (1) interval AHP (I-AHP) (Laarhoven and Pedrycz, 1983; Sugihara and Tanaka, 2001; Sugihara et al., 2004), (2) triangular fuzzy AHP (Tri-AHP) (Tsaur et al., 2002; Ertugrul and Tus, 2007), (3) and trapezoidal fuzzy AHP (Tra-AHP) (Chen and Guo, 2006; Su and Tung, 2014; Zou et al., 2013).

Fig. 7 shows the membership sets of the fuzzy AHP for a metro system risk assessment. As shown in Fig. 7(a), I-AHP uses an interval number instead of a crisp number, which allows fluctuation in the relative importance of intervals within $[w_1, w_2]$ (Laarhoven and Pedrycz, 1983; Sugihara and Tanaka, 2001; Sugihara et al., 2004). The weights of assessment factors are described in Eq. (1). Tri-AHP uses a pair of triangular fuzzy numbers to express the degree of connection between assessment factors (see Fig. 7b). The membership function of Tri-AHP is described in Eq. (2), which assigns each object a class of membership ranging from zero to one (Tsaur et al., 2002; Ertugrul and Tus, 2007). The membership function of Tra-AHP is defined in Eq. (3). As shown in Fig. 7c, if $m_2 = m_3$, M is a triangular fuzzy number; if $m_1 = m_2$, and $m_3 = m_4$, M is an interval number; if $m_1 = m_2 = m_3 = m_4$, M is a crisp value. Therefore, Tra-AHP can arithmetically handle and intuitively interpret fuzzy numbers in a variable way (Chen and Guo, 2006; Zou et al., 2013; Su and Tung, 2014; Lyu et al., 2018a). Fuzzy AHP methods provide a wider application range than original AHP, and are able to reflect random and stochastic systems.

$$w = [\alpha w_1 + \beta w_2] \tag{1}$$

where w_1 and w_2 are the weights of the lower weight and upper weight of I-AHP; α and β are two coefficients of the interval weights; w is the interval weight of I-AHP.

$$\mu(d) = \begin{cases} 1 & (M_1 \geqslant M_2) \\ 0 & (l_2 \geqslant u_1) \\ \frac{l_2 - u_1}{(m_1 - u_1) - (m_2 - l_2)} & (\text{otherwise}) \end{cases} \tag{2}$$

where M_1 and M_2 are triangular fuzzy numbers; m_1 and u_1 are medium number and right number of M_1; l_2 and m_2 are the left number and medium number of M_2; $\mu(d)$ is the intersection distance between M_1 and M_2.

$$\mu_M(x) = \begin{cases} 0, & (x < m_1) \\ \frac{x - m_1}{m_2 - m_1}, & (m_1 \leqslant x \leqslant m_2) \\ 1, & (m_2 \leqslant x \leqslant m_3) \\ \frac{m_4 - x}{m_4 - m_3}, & (m_3 \leqslant x \leqslant m_4) \\ 0, & (x > m_4) \end{cases} \tag{3}$$

where m_1 and m_4 are the lower and upper limits of a trapezoidal fuzzy number; m_2 and m_3 are the interval variables of a trapezoidal fuzzy number, $\mu_M(x)$ is a trapezoidal fuzzy number corresponding to x.

4.3. Risk assessment from qualification to quantification

The fuzzy AHP method can provide a qualitative flood risk assessment for metro systems. Based on the assessment result, quantitative simulation is applied to analyse metro lines with high risk levels. The flood risk of a metro system is assessed by the risk level within 500 m along the metro line (Lyu et al., 2018a). Fig. 8 shows the framework for the inundation risk assessment of a metro system. This procedure is defined as “from qualification to quantification”. For the quantification analysis, the urban rainstorm model SWMM is incorporated into a GIS to simulate a scenario analysis. SWMM is a useful tool for modelling urban drainage systems (Zhu et al., 2016b; Wu et al., 2017c), but it cannot reflect the real situation of surface runoff. To model the surface runoff, a spreading algorithm developed in FORTRAN is proposed, and is incorporated into a GIS to obtain the spatial distribution of inundation depth and range. In the quantitative analysis, scenario-based inundation analysis is used to predict the inundation risk for metro stations. Finally, both the qualitative analysis and quantitative analysis are applied to verify the inundation risk for metro system.

5. Case study

5.1. Flood risk assessment of Guangzhou metro system

To demonstrate the application of the proposed method, Guangzhou Metro System is used as a case study. Fig. 9 shows the flowchart of the assessment procedure for the metro system. In this procedure, the primary step is the establishment of assessment structure, which has critical effects for the reliability of assessment results. In this case study, I-AHP method is used to calibrate the weights of factors. The normalized factors combined with their corresponding weights are integrated into GIS to obtain a spatial distribution of regional flood risk level. Finally, the risk level in the range of 500 m around a metro line is extracted from the regional flood risk level to assess the flood risk of metro system. The detailed weight calibration process using I-AHP can be found in Lyu et al. (2018a).

5.2. Regional distribution of flood risk

Based on the data sources and their corresponding weights, the spatial distribution of regional flood risk level can be obtained using

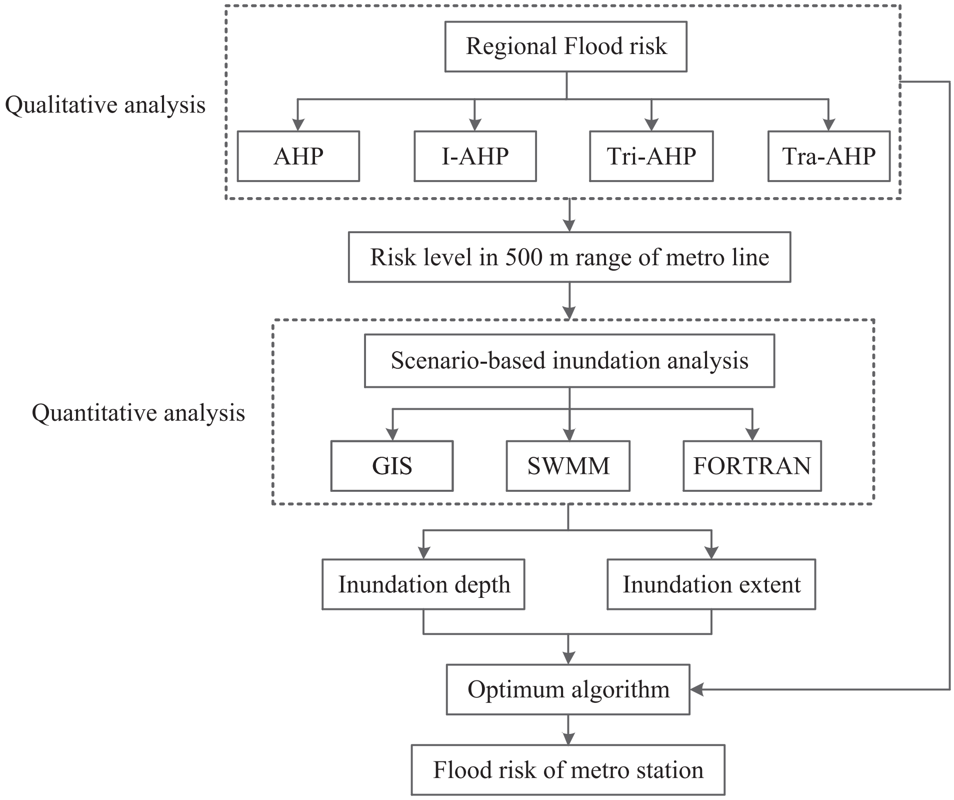

Fig. 8. Approaches for flood risk assessment for metro systems.

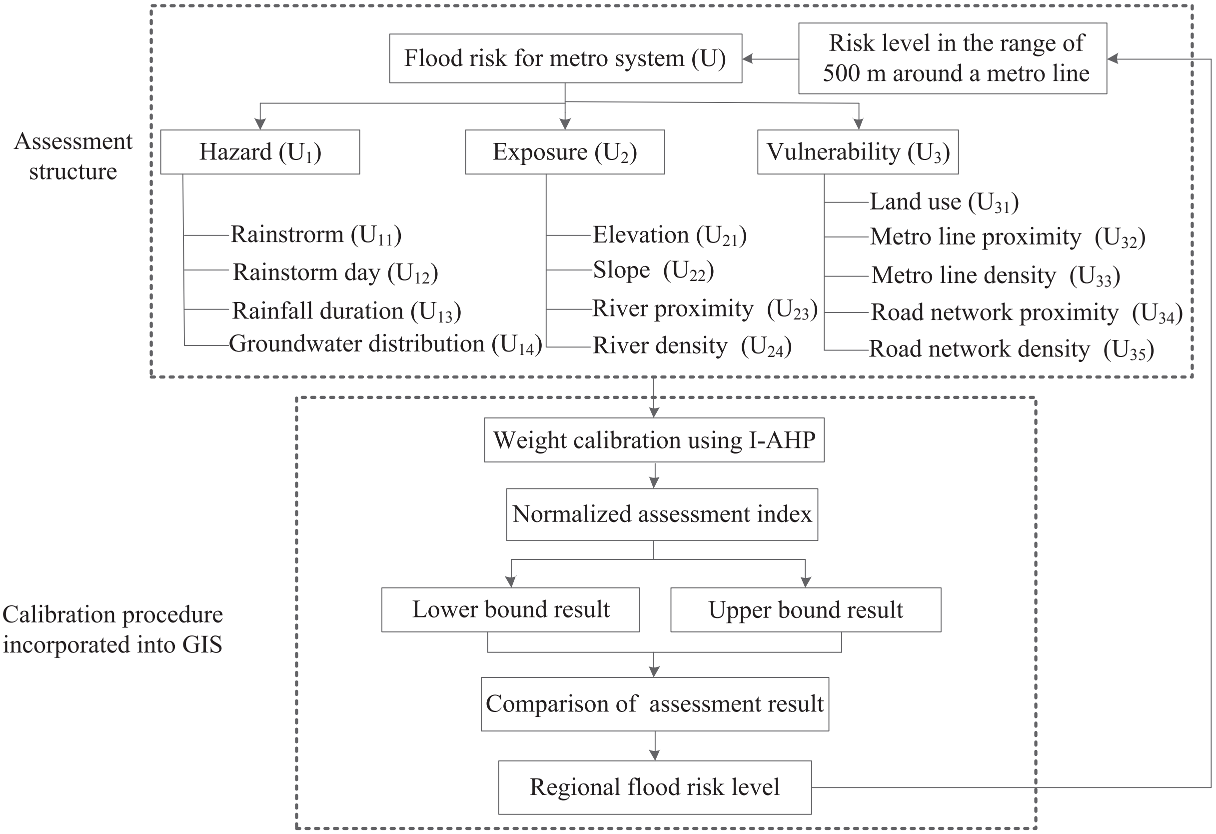

Fig. 9. Flowchart of assessment procedure for metro system.

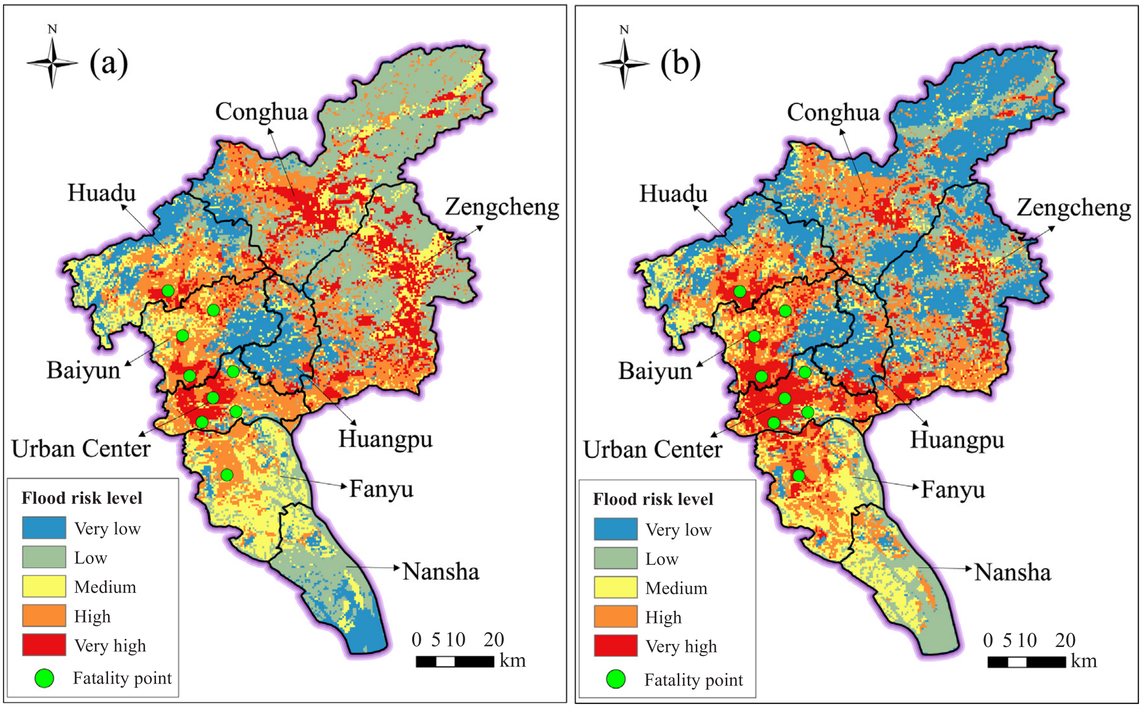

Fig. 10. Spatial distribution of regional flood risk level: (a) AHP; (b) lower bound I-AHP; (c) upper bound I-AHP (After Lyu et al., 2018a).

GIS tools. Fig. 10 shows the spatial distribution of regional flood risk level from I-AHP method. As shown in Fig. 10, the spatial distributions from the lower bound and upper bound of I-AHP are very similar, but the very high-risk level from the upper bound is larger than that from lower bound. Fig. 10 also shows the fatality locations in the flood event happened on May 10th, 2016 in Guangzhou City, which caused nine deaths (Lyu et al., 2016). As shown in Fig. 10, the results of very high-risk level by I-AHP match well with the distribution of fatality locations. Therefore, the I-AHP model can provide a more accurate indication of regional flood risk, guaranteeing the reliable assessments for the metro

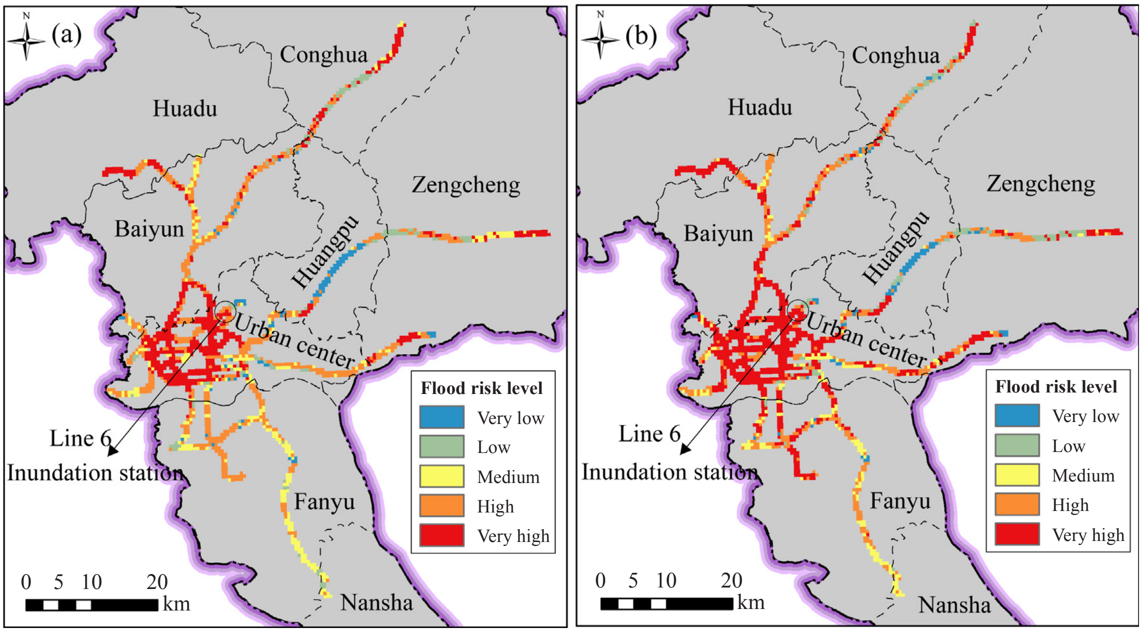

Fig. 11. Flood risk level in the range of 500 m around metro lines of Guangzhou Metro from AHP and I-AHP: (a) AHP; (b) lower bound I-AHP; (c) upper bound I-AHP (After Lyu et al., 2018a).

system.

5.3. Flood risk of metro system

After assessing regional flood risk level, the risk level along the metro line can be mapped using GIS tools for the risk assessment of the metro system. Fig. 11 shows the flood risk level in the range of 500 m around the metro lines using I-AHP. In the flood event happened on May 10th, 2016, Changpan station of metro line 6 was soaked by rainwater with the water depth of 0.5–0.8 m (Lyu et al., 2016). The assessment results by lower bound shows that Changpan Station is at a high-risk level, whereas the upper bound assessment results by I-AHP shows that Changpan Station is at a very high-risk level. This comparison shows that I-AHP provides an interval assessment results, which is more reasonable for flood risk of the metro system.

6. Perspectives of countermeasures

6.1. Existing measures

In response to severe inundation, the first countermeasure is to effectively prevent floodwater entering into metro stations (Jakoubek, 2007). Various waterproofing facilities at all tunnel openings should be developed and installed (e.g., tunnel entrances, ventilation openings, underground station entrances). Underground station entrances are expected to suffer from the most severe damage. According to Aoki et al. (2016), conventional waterproofing doors (hinged doors that apply positive pressure against floodwater pressure) can hardly improve all Tokyo metro station entrances since most of these entrances were situated on sidewalks, which have many obvious spatial restrictions. Therefore, new doors that fit the environment of individual entrance should be developed (e.g., counter-pressure doors, hinged double doors, shutter, and bi-fold doors). Fig. 12 shows some countermeasures for protecting metro entrances from floodwater. The water stop plate (Fig. 12a) is used to control flooding if it is less than 1 m deep. The water stop plate is initially set at the lowest level (approximately 35 cm high) to ensure that passengers can evacuate during the early stage of flooding. The waterproof door (Fig. 12b) is used to control flooding of up to 2.0 m deep. The waterproof door was widely reported by various media because it was the first waterproofing facility for flood control. The waterproof door was tested for leakage using a high-pressure jet, and confirmed its capacity against the leakage (Aoki et al., 2016). These countermeasures can be applied in metro station entrance with a high inundation risk in China.

Besides, another important countermeasure is to efficiently drain the floodwater from metro stations into sewerage system. The functional drainage system of tunnels must be kept in good working condition during flood emergence (English, 2016). In 2014, West Virginia University developed a solution utilizing one or more inflatable plugs that could be placed at different locations along a tunnel (Sosa et al., 2014). To protect tunnels, the inflatable plugs are similar to the inflatable dams used as diversion structures for flood control (Sosa et al., 2014).

6.2. Modern techniques for early warning

Fernando (2016) applied GPS, RS, and GIS to develop an early warning system for mitigating urban flood disasters. Elkhrachy (2017) applied GIS and RS techniques to manage flash floods in Najran Wady, through modelling flash flood events and calculating water surface profiles over the length of the modeled stream. Song et al. (2017) reviewed the trends and opportunities of BIM-GIS integration in the construction industry from a spatial-temporal statistical perspective. According to Song et al. (2017), the application of BIM-GIS integration requires systematic theories, including deep utilization of mathematical modelling approaches and spatial-temporal modelling in GIS and BIM simulations. Du et al. (2015) applied BIM to manage all the information on metro construction dynamically and applied GPS to monitor the high-risk construction equipment. The utilization of BIM and GPS in management mitigated the risks related to underground construction. It is possible to provide a visualization of an underground space. Even more, the application of early warning systems in underground metros is expected to monitor the occurrence of floods (Du et al., 2015).

BIM is an innovative approach to address deficiencies in safety risk identification (Hardin and McCool, 2015). The implementation of BIM provides potential advantages for safety management in construction design and planning of tunnel construction (Zhang et al., 2016). BIM technology also has been used to design metro stations by restrictive

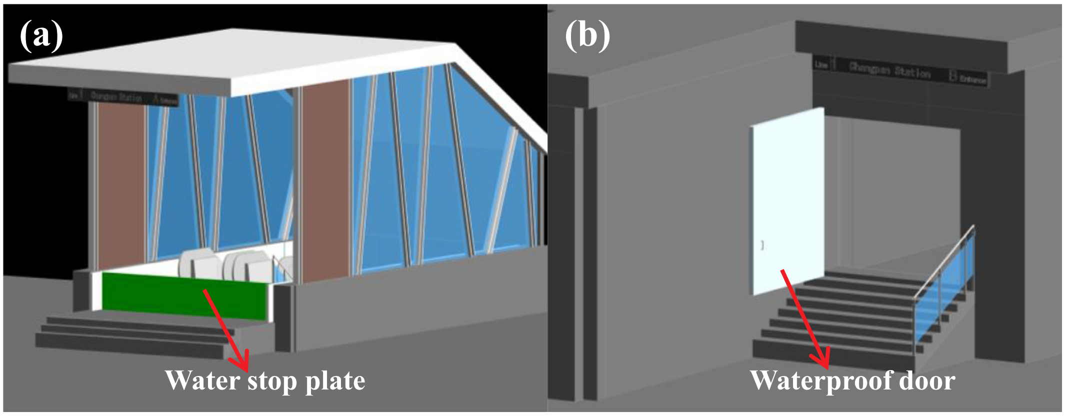

Fig. 12. Countermeasures for metro entrance protection from floodwater: (a) water stop plate and (b) waterproof door.

conditions (Pu and Wei, 2014). In addition, the utilization of GPS and GIS techniques in tunnel construction can achieve a dynamic management with three-dimensional geographic spatial location information for visual management of all information. Therefore, the integration of GIS, GPS, and BIM for the development of early warning and risk management systems can allow managers to dynamically monitor the multiple risks of inundations in metro tunnels (Du et al., 2015).

RS and permanent scatter interferometry synthetic aperture radar (PSInSAR) techniques are widely used to monitor the development of geohazards (Anderson, 2013; Czikhardt et al., 2017; Liu et al., 2018). They can also be used to identify underground objects and discontinuities (e.g., metro tunnels and tubes). Vanus et al. (2017) proposed a new method for improving the signal-to-noise ratio of remote sensing devices, which use electromagnetic waves for detection of underground objects. Comerci et al. (2015) provided an effective PSInSAR tool for local governments to monitor ground and building behaviour during underground construction, and to provide possible prevention activities. The application of these modern techniques could help in monitoring the occurrence of flood disasters in underground space.

7. Conclusions

This work presents a state-of-the-art review of inundation risk for mega-city infrastructure, including risk assessment methods and countermeasures to keep sustainability of total environment for mega-cities. The following conclusions can be drawn.

1. Regional flood risk assessment methods in literatures are divided into four types: statistical methods, multi-criteria analysis, GIS and RS techniques, and scenario-based analysis. Risk assessment approaches for underground infrastructure are divided into mathematic-based fuzzy theory and numerical-based simulation, both of which have been used for other hazards but seldom for flood disasters.
2. According to the review on risk assessment methods, a perspective of the approaches for inundation risk assessment in underground infrastructure (e.g., metro systems) is proposed. A collective approach from this perspective includes the following two procedures: (*i*) from regional to local and (*ii*) from qualification to quantification. In the first procedure, flood risk is firstly assessed at the regional level, and then it is assessed from the flood risk levels within 500 m of a metro line. In the second procedure, flood risk level is assessed qualitatively at first. Then based on the qualitative results, scenario-based inundation analysis is conducted to make a quantitative prediction of inundation before flooding.
3. The case study of flood risk assessment in Guangzhou Metro System demonstrates the application of the proposed perspective methods. The results show that the densest distributions of metro lines are in region with high level of flood risk. The fuzzy AHP can indicate the region with high-risk levels.
4. The proposed perspective for mitigating floods in underground metros can be summarized as an iterative circular procedure, including risk assessment analysis and countermeasures. The countermeasures for dealing with inundations in underground infrastructure include floodwater protection and its drainage. In addition, the integration of GIS, GPS, and BIM for early warning and risk management systems is recommended to dynamically monitor the multiple risks of inundations in metro tunnels.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tust.2018.10.019.

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