The susceptibility assessment of multi-hazard in the Pearl River Delta Economic Zone, China

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Abstract

The multi-hazard susceptibility assessment can provide a basis to decision-makers for land use planning and geo-hazards management. The main scope of this paper is to assess multi-hazard susceptibility and identify susceptibility area by using an integrated method of the Analytic Hierarchy Process (AHP) and the Difference Method (MD) within MapGIS environment. The basic principle of this method is to predict future geological hazards based on occurrence mechanism and formation conditions of geological hazards and the geological conditions within the study area. Typical geo-hazards susceptibility are separately assessed by applying Analytic Hierarchy Process (AHP). The multi-hazard susceptibility is completed by synthesizing individual geo-hazards susceptibility result with the Difference Method (MD), the multi-hazard susceptibility map is generated by utilizing MapGIS platform. The multi-hazard map can provide decision-makers with visual information for geo-hazards prevention, which reduce confusion of decision-makers on high number of individual geo-hazard maps. The study area was categorized into high susceptibility zone, moderate susceptibility zone, low susceptibility zone, and insusceptible zone, accounting for 16.5%, 41.6%, 33.8% and 8.1% of the total study area, respectively. The multi-hazad susceptibility result can be combined with other conditions to provide decision- makers with theoretical basis for geo-hazards management and planning of development.

Key words: susceptibility assessment; mul-hazards; Analytic Hierarchy Process (AHP) - Difference Method (DM); MapGIS; The Pearl River Delta Economic Zone

1. Introduction

Geological hazards occur frequently, and the types of disasters in China are various (National Disaster Mitigation Center Disaster Information Department, 2009), especially southwest region of China (Tang and Wu, 1990). The Pearl River Delta Economic Zone is the transitional belt and sensitive belt of geological environment, nears the South China Sea, characterized by strong land-ocean interaction, widely distributed Quaternary, complex geological structure, and various landform, where it is susceptible to cause geological disasters (Li, 2012). With the rapid economic development for the Pearl River Delta Economic Zone, the strength of development and utilization for geological environment trends to increase, the frequency and intensity of geological hazards intensifies rapidly, which has a great threaten upon people's lives and property (Zhang, 2012). The occurrence of geological hazards seriously restricted the urban development and the sustainable development of human society (Unitto and Shaw, 2016). According to geological survey result, geo-hazards occurred in the Pearl River Delta Economic Zone mainly include collapse, landslide, debris flow, ground subsidence, karst collapse, water and soil erosion and seawater intrusion, the scale of debris flow is small, so it is not considered as object of study in this paper. Therefore, in order to minimize the economic loss and reduce threaten on people's lives and property, management of geological hazards is essential. Thus, it is very meaningful to evaluate geological hazards susceptibility and identify different susceptibility areas for prevention and management of geological hazards.

Since geological hazards are a complex phenomena, currently, various researches have focused on a single geological hazard research (Komac, 2006; Pradhan et al., 2016; Wang et al., 2015; Zhou et al., 2002). But, one region may suffer from more than one geological hazard. The multi-hazard susceptibility assessment that consists of relation between different hazards is an important tool for geological hazards management and urban planning. The United Nations (UN, 2002) has emphasized the significance of multi-hazard assessment and referred that "it is an essential element of a safer world in the twenty-first century". However, multi-hazard susceptibility assessment is a complex process and confronts with challenges. At early stages, qualitative assessment methods were widely used to evaluate geological hazards susceptibility (Bijukchhen et al., 2013; Cui et al., 2004; Degg, 1992; Liang et al., 2011;

Zhou et al. 2002), which are based on statistical analysis for the scale and density of occurred geological hazards, but it is difficult to describe the affect of different influencing factors on geological hazards. In recent years, with development of science and technology, the methods that combines qualitative and quantitative analysis are widely used to evaluate geological hazards susceptibility (Lee et al., 2018; Wang et al., 2015; Yilmaz, 2009). One widely used method for susceptibility assessment is the Analytic Hierarchy Process (AHP) (Karaman, 2015; Karaman and Erden, 2014; Komac, 2006; Peng et al., 2012; Rozos et al., 2011). The AHP is a multiple criteria decision-making that combines qualitative and quantitative factors for ranking and evaluating alternative scenarios, among which the best solution is ultimately chosen (Satty, 1980; Satty, 2008). Preventive measures for different geological hazards are various, and their damage on environment and people's lives and property is not neutralized. Thus, multi-hazard susceptibility assessment is completed by synthesizing all individual geological hazards susceptibility result with the Difference Method. The major principle of the Difference Method is that the multi-hazard susceptibility in this a unit is considered high, as long as there is a kind of geological hazard are under high susceptibility in specific evaluation unit.

In this paper, a new method that integrated the Analytic Hierarchy Process (AHP) and the Difference Method is proposed to assess multi-hazard susceptibility. Individual hazard susceptibility is assessed with via of the Analytic Hierarchy Process (AHP) and spatial analysis of MapGIS, based on the geological hazards investigation and geological environmental conditions of the study area. The Difference Method is used to assess multi-hazard susceptibility by synthesizing the five aforementioned geohazard susceptibility assessments. Moreover, a multi-hazard susceptibility map is produced with MapGIS. The multi-hazard susceptibility map will benefit local governments in making policies on urban development and infrastructure layout, and it also offer more accurate and effective theoretical guide to land use planning and site selection of major projects, coming true the maximum utilization of limited resources and the maximum economic efficiency with limited environment.

2. The study area

2.1 Natural geographical conditions

The Pearl River Delta Economic Zone, with a total area of 41698 km^2, is located in the south-central Guangdong Province, China (Fig.01), nears the South China Sea, between 21°43' ~ 23°56' N latitude and 112°00' ~ 115°24' E longitude. It includes 9 prefecture-level cities.

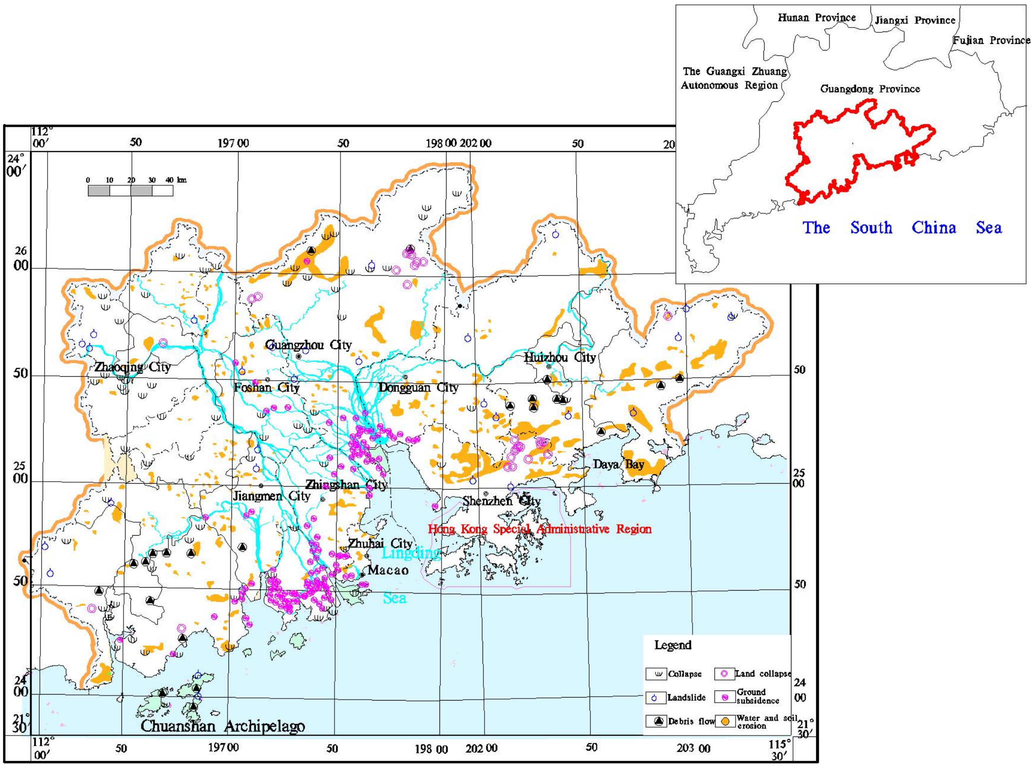

Fig.01 The spatial distribution map of geo-hazards in the study area

The study area belongs to subtropical monsoon climate, characterized by mild, humid and abundant rainfall. The rainfall is characterized by high precipitation, more rainy days, stronger seasonal rainfall, and uneven spatial distribution under influence of monsoon climate. The annual precipitation is reported as about 1800-2200mm (Fig.02).

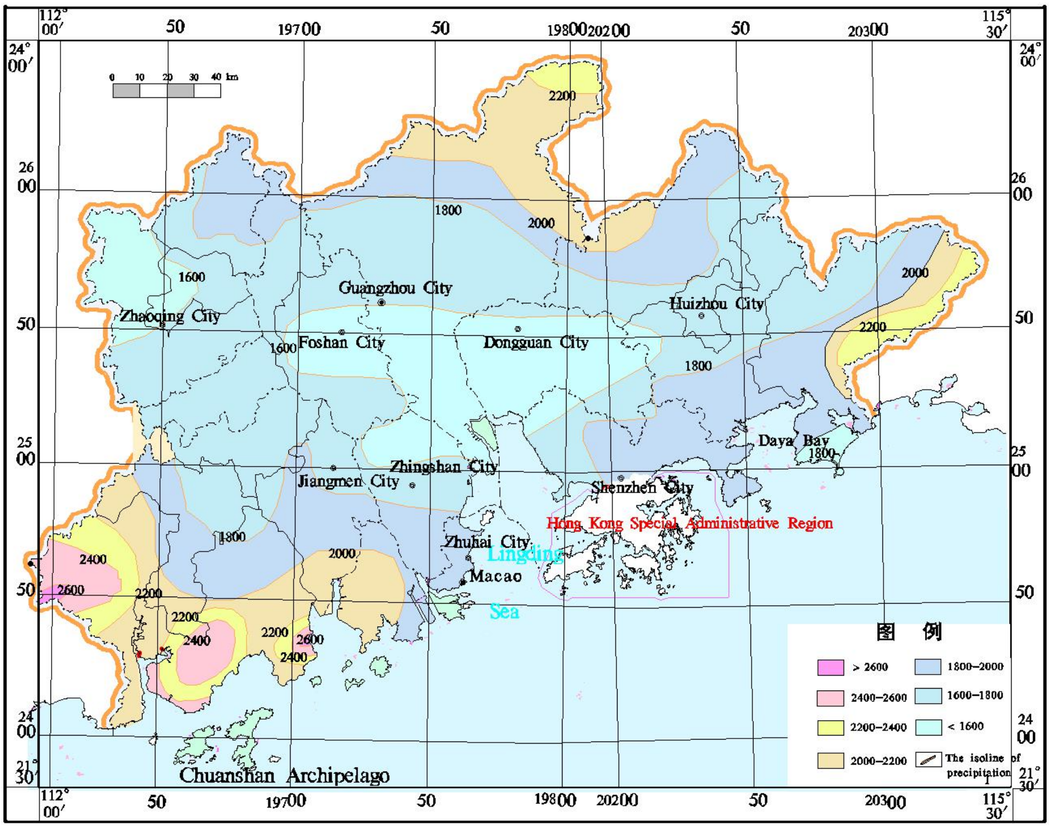

Fig.02 The spatial distribution map of precipitation for the study area

The topography is dominated by the Pearl River delta plain, surrounded by intermittent mountain and hills, such as Gudou Mountain, Tianlu Mountain and Luofu Mountain. The terrain is flat, ranging in altitude from -0.2 m to 0.9 m in the plain area. Based on the different genetic type, the geomorphic units are divided into 12 kinds of level II geomorphological units, consisting of erosion and denudation middle mountains, erosion and denudation low mountains, erosion and denudation hills, erosion and denudation platforms, karst hills, volcanic hills, delta plain, alluvial and marine deposition plain, alluvial plain, alluvial and dilluvial plain, marine deposition plain and islands.

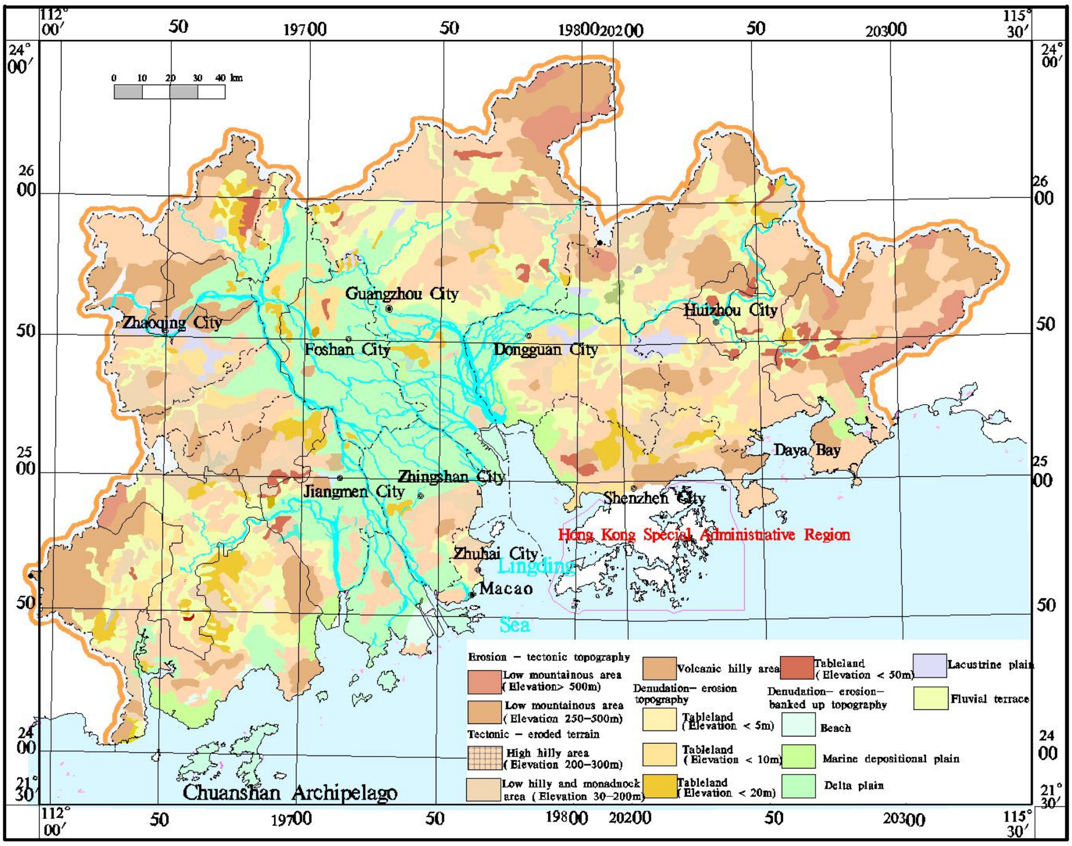

Fig.03 The topography map of the study area

2.2 Geological conditions

2.2.1 Essential geological condition

Development of the strata is relatively complete, and it is characterized by complicated types and the wide distribution. The stratigraphic age of the outcropped bedrock ranges from the Metamorphic rocks to the Quaternary loose debris deposition rocks, the outcropped strata is mainly Quaternary, followed by the Sinian, Cambrian, Devonian, Carboniferous, Jurassic and Cretaceous, and the distribution of Mesoproterozoic, Ordovician, Permian and Paleogene are sporadic (Fig.04). The area of outcropped Quaternary loose accounts for 3/4 of the strata area, the outcropped bedrock area accounts for 1/4 of the strata area. The Magmatic rocks is dominated by intrusive rocks, volcanic rocks only develop in small areas. The area of Magmatic rocks accounts for about 30% of the entire study area.

The study area belongs to the South China fold belts, the Northern and Central Guangdong depression belt, and the main depression is the Sanshui Depression Basin. Some large fractures develop in the study area (Fig.04). These large fractures are characterized by multiple phases of activity, especially since the late Tertiary, which have affect on formation and evolution of the Pearl River Delta, structure development and crustal stability.

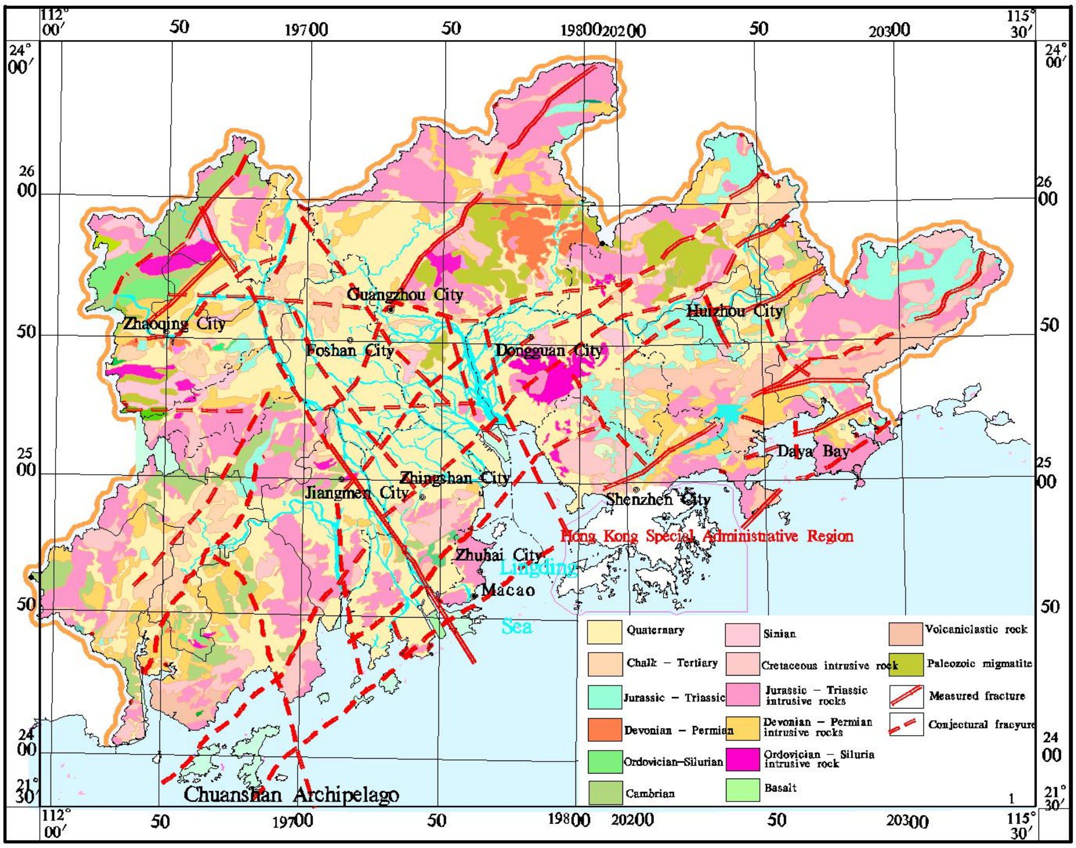

Fig.04 The geological map of the study area

2.2.2 Hydrogeological conditions

In the study area, groundwater is divided into three types: loose rock pore water, carbonate karst water and bedrock fissure water, hydrogeological characteristics are shown in Fig.05.

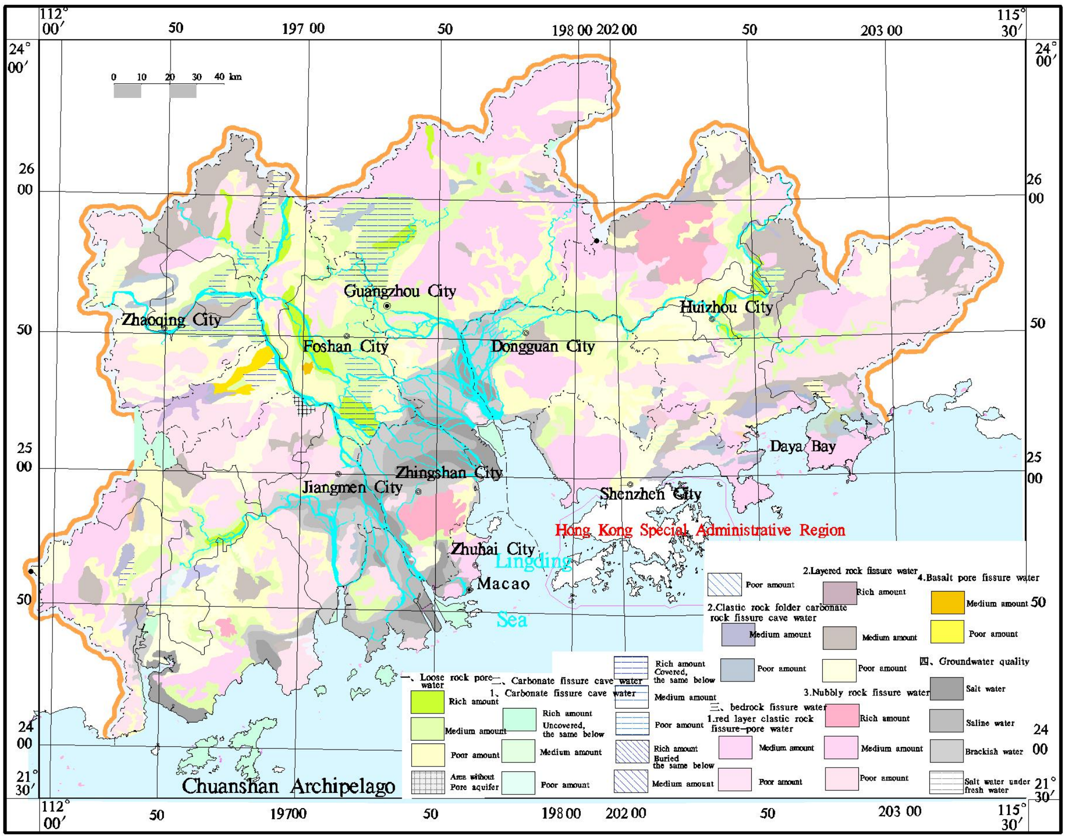

Fig.05 The hydrogeological map of the study area

2.2.3 Engineering geological condition

The rock-soil body is restricted by the topography, strata, lithology, geological structure, and it is also affected by the hydrogeological conditions, natural geological conditions. Based on the nature, origin and structural features of the rock-soil body, the rock-soil body is divided into three types: magmatic rocks, metamorphic rocks and sedimentary rocks. In addition, it can be also divided into gravel soil group, sandy soil group, clay soil group and intrusive rock residual soil group, extrusive rock residual soil group and metamorphic rock residual soil group (Fig.06).

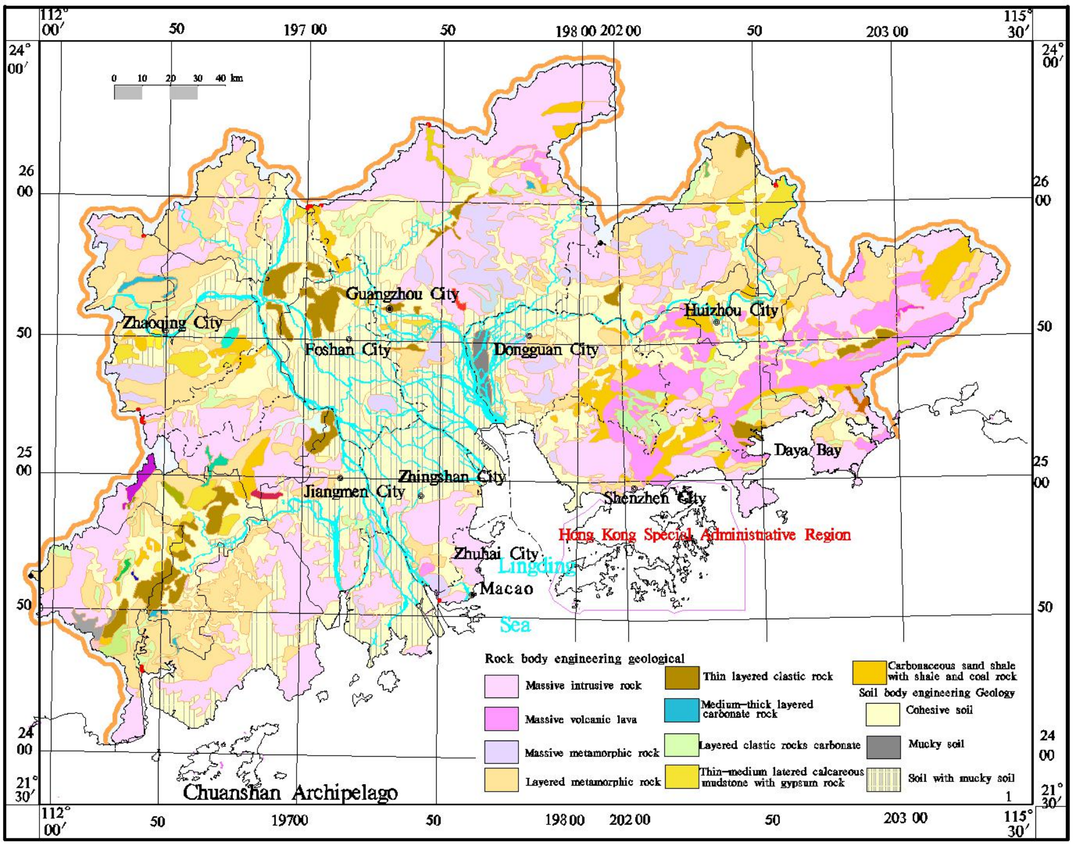

Fig.06 The engineering geological map of the study area

2.3 The major geological hazards

According to a field geological survey, typical geological hazards that occurred within the study area mainly consist of collapse, landslide, ground subsidence, karst collapse, water and soil erosion, and seawater intrusion. As of 2014, there are 52 large-scale collapses, 35 landslides and 5 debris flow have been found in the study area. In addition to, 129 ground subsidence hazards occurred in the study area, among of them, there are 76 ground subsidence with less than 10 cm of accumulative subsidence are found. Water and soil erosion is fragmented distributed in mountainous areas, hilly areas and tableland areas, which are characterized as karst desertification, granite and small vegetation coverage. In addition, water and soil erosion is widely distributed in Longgang District, Shenzhen City and Huadu District, Guangzhou City. According to statistics, water and soil erosion covers an area of 2300km^2, accounting for about 4.8% of the total land area. The seawater intrusion mainly occurred in the Pearl River Estuary area. The scope of the annual seawater intrusion spread to the inland area (Yaxi Town - Hualong Town - Humen town area), and it possibly reached Guangzhou City during the drought years. According to the research (Liu 2004), the driving forces of seawater intrusion for the study area are mainly tides and runoff, followed by saltwater tides. The distribution for geological hazards is shown in Fig.1.

2.4 Human activity characteristics

At present, woodland covers a area of 20348.6 km^2, accounting for 48.8% of the total study area, cultivated land, garden plot and construction land account for 38.0%, 6.1% and 6.1%, respectively. Current state of land use within the study area can be shown in Fig.7, vegetation type can be shown in Fig.8. Except for the Pearl River Delta plain located in the hinterland, other lower-lying hills or platforms can be reclaimed into dry land that is suitable for planting various crops, fruit trees and economic trees. In recent years, with the rapid economic development, the land use structure has changed significantly. The area of cultivated land and garden plot are declining year by year, and the construction land rapidly expand. In the background of rapid economic and social development, the land use structure still will has a great change in the future, and "the expansion of urban construction land, the massive loss of cultivated land and garden plot" will are the main features.

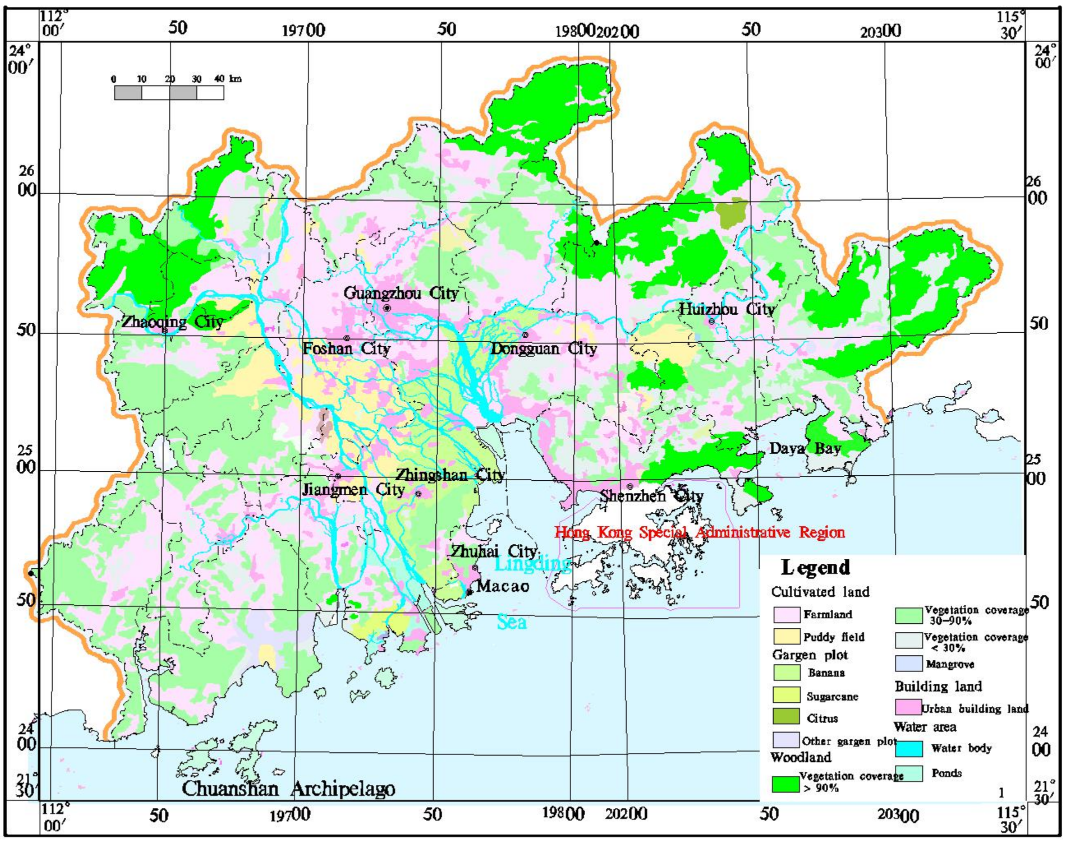

Fig.07 The land use map of the study area

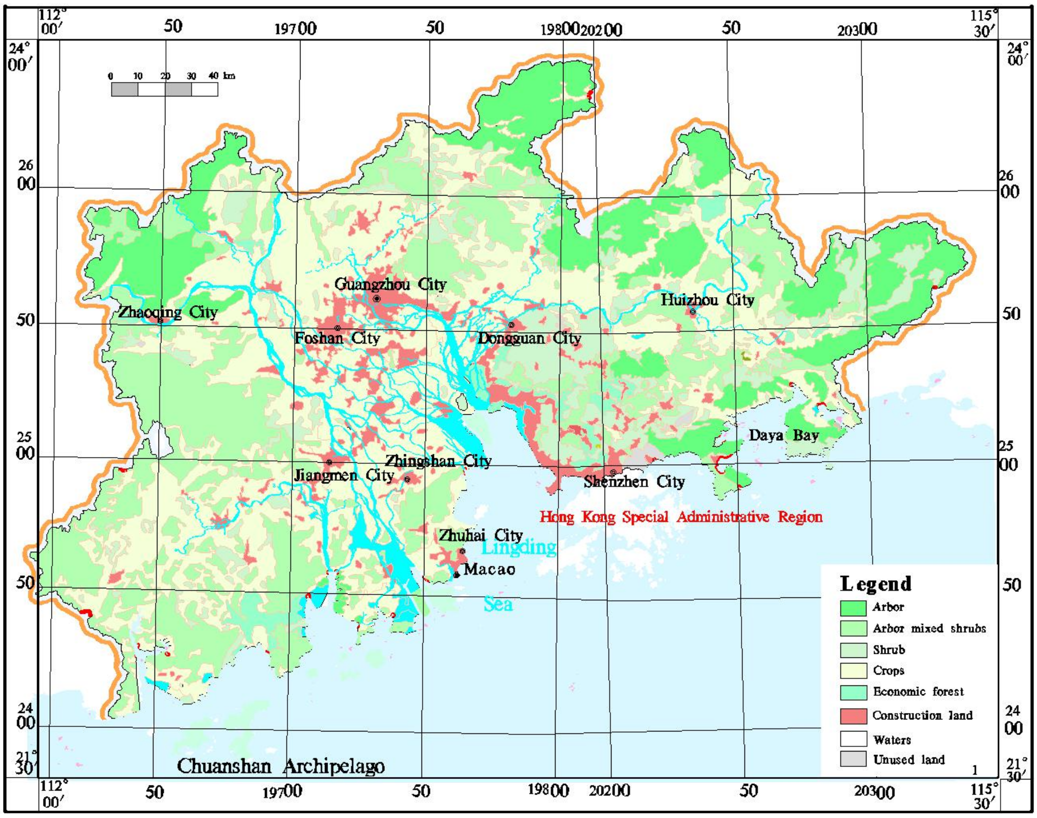

Fig.08 The vegetation type map of the study area

3. Materials and methods

3.1 Source of Data

Data sources were provided by Geological Survey Center, Wuhan. Database was obtained by digitizing the existing maps of the study area, collected from Geological Survey Center, Wuhan.

3.2 Methods

Geological hazards causal factors

(1) Karst collapse causal factors

Obtained research results (Su, 1998; Wang, 2001) show that the formation of karst collapse is mainly affected by degree of karst development, overburden characteristics, geological structure, and groundwater activities. Karst development is basis and prerequisite for formation of karst collapse. Overburden is material basis for formation of karst collapse and controls its formation in certain degree. Thick overburden can effectively disperse pressure of the soil body on the soil hole. Compared with the thinner overburden, the thicker overburden is less prone to karst collapse, and the scale and form of karst collapse also are closely connected with the overburden thickness. Groundwater activities is the main triggering factor of formation of karst collapse. Geological structure can control the development of karst and can provide a good site for soil erosion, and the spatial distribution of karst development is also closely related to the geological structure. In general, the stretching direction of the karst collapse area is consistent with that of the geological structure (Fu, 2009). Based on the above analysis and geological environmental conditions for the study area, the causal factors of karst collapse include the degree of karst development, lithology, overburden thickness, aquifer water yield property and the distance to the fault.

(2) Landslide and collapse causal factors

Collapse differs from landslide obviously in the form of occurrence, scale and perniciousness, but there are also internal relations between them, which make them have strong consistency in temporal and spatial distribution. Collapse and landslide belong to the problem of slope rock mass instability, they often associated with each other in the cause of formation. Landslide is closely related with collapse, and they usually occur accompanied. Collapse and landslide occur under the same geological tectonic setting and the same stratigraphic lithology conditions, with the same triggering factors. So the causal factor for occurrence of collapse maintain basically consistency with that of landslide. Thus, this paper carries out the susceptibility assessment of collapse and landslide.

According to the statistical analysis of geological hazards, the spatial distribution characteristics of collapse is affected by topography, geological structure, stratigraphic lithology, climatic conditions and hydrological conditions. Moreover, there is a positive correlation between the annual number of collapse and temporal distribution of precipitation (Deng, 2008). Topographical conditions are the prerequisites to formation of landslide hazards (Li, 1996). Topography differences provide gravitational potential energy for instability movement of rock and soil body. Geological conditions, characteristics of rock and soil body and hydrological conditions also play key role in controlling slope stability. Based on analysis of formation conditions and development characteristics of collapse and landslide which occurred within the study area, main causal factors of collapse and landslide include topography, lithology, the distance to fracture and precipitation.

(3) Ground subsidence causal factors

The mollisol is prerequisite factor for controlling the formation of ground subsidence, so the area distributed with moilisol is considered as study range for ground subsidence susceptibility. Geological settings are primary internal factor. The mollisol is distributed in the entire delta alluvial plain, and its thickness trends to increase from the top to the front of the delta. The ground subsidence frequently occurs in the central and southern coastal areas of the study area, where the mollisol is characterized as large thickness, shallow depth and new age of deposits formation. In general, the degree of ground subsidence is closely related to the characteristics of millisol, primarily including the age of millisol deposition, the thickness of millisol layer, and depth of milliso. Hydrogeological conditions are triggering factor for formation of ground subsidence. The ground subsidence mainly occur in clay layer, and it is extremely sensitive to the change of groundwater table. Thus, investigating the distribution characteristics of groundwater is prerequisite to study ground subsidence. Stronger aquifer water yield property means larger allowable exploit amount of groundwater, that is, the susceptibility of ground subsidence is larger. According to survey result, it is found that ground subsidence mostly occurred in the groundwater runoff area, along the stretching direction of fracture. According to the above analysis and geological investigation result, we can found that the age of millisol deposition, the thickness of millisolde position, aquifer water yield property and the distance to fracture are main causal factors of ground subsidence.

(4) Water and soil erosion causal factors

Based on analysis of the occurrence mechanism and formation conditions of water and soil erosion, the casual factors of water and soil erosion consist of topography, soil type, vegetation type, precipitation and the density of of river network. Soil is the material basis for water and soil erosion to occur, it is also the object of erosion. Water and soil erosion is mainly distributed on granite-developed soil within the study area. The distribution of latosolic red soil is the mostly wide within the study area, accounting for 44.8% of the land area, follow by is paddy soil, accounting for 40.20%. The parent material of latosolic red soil is mainly granite, the granite is characterized by thick weathering soil, loose structure and poor soil viscosity. After destroying the original vegetation and slope conditions, water and soil erosion is caused under the long-term erosion and scour of rainfall. Rugged topography is the direct factor to cause water and soil erosion, the steeper the slope is, the shorter the confluence time is, the larger the runoff energy is, the stronger the erosion of water on the land is.

Water and soil erosion mainly occurred in hilly area for the study area. The vegetation cover is critical factor for controlling the occurrence of water and soil erosion, because it can prevent soil erosion, mainly including reduction for rainfall energy, water retention and anti-erosion. Rainfall is the direct dynamic factor for causing water and soil erosion. The annual precipitation 1600 mm within the Delta plain area is less than that of the surrounding hilly area, with annual precipitation of 2000-2600 mm.

(5) Seawater intrusion causal factors

Hydrodynamic conditions and hydrogeological conditions are two essential factors for controlling the occurrence of seawater intrusion, the hydrodynamic condition means that there is a certain head pressure between seawater and fresh water, hydrogeological conditions is that there is a hydraulic relation between the seawater and the land aquifer. When these two conditions all are available, seawater intrusion trends to occur. Seawater intrusion was caused by the change of hydrodynamic conditions of the coastal groundwater, major dynamics are tides and runoff. Seawater intrusion only occurred in winter and spring within most of the coastal areas of the study area, because precipitation is small, groundwater is not recharged in time, resulting to lowing of groundwater table (Sun, 2011). So over-exploitation of groundwater can aggravate seawater intrusion. According to geological conditions and the current situation of seawater intrusion. Topography, the type of Quaternary sedimentary rock, groundwater table and precipitation are main influencing factors of seawater intrusion susceptibility.

Application of the analytic hierarchy process

The AHP method, pioneered by Saaty in the 1970s, is a multi-objective decision analysis method that combines qualitative and quantitative analysis. A detailed description of the AHP method is available in Saaty (1980). The procedure for using this method can be summarized as follows (Saaty, 2008): (1) Structuring the decision hierarchy, the assessment object is divided into a few structure layers, namely, the target layer, criterion layer, and element layer. (2) Constructing a series of pair-comparison judgment matrices between factors, and the pairwise comparison employs an underlying nine-point recording assessment to rate the relative importance on a one-to-one basis of each factor. (3) The consistency of pairwise comparison matrix between factors should be measured by the consistency ratio (CR), which is the consistency index of the matrix. And the value of the CR should be no higher than 0.1. CR can be calculated by Eq.(1):

$$CR=CI/RI \quad (1)$$

where RI is the mean random consistency index, which depends on the order of the matrix given in Table 1; CI is the consistency index used to measure the deviation of the matrix, as expressed in Eq.(2):

$$CI = \frac{\lambda_{max} - 1}{n - 1} \quad (2)$$

Where λ_{max} is the largest or principal eigenvalue of the matrix and can be easily calculated from the matrix, and n is the order of the matrix.

<Table 1>

(4) The factor weights are obtained through matrix operations, sorting operations and a consistency check.

The susceptibility value of individual geological hazard is computed according to the following formula Eq.(3):

$$SI = \sum_{i=1}^{n} R_i W_i \quad (3)$$

Where SI denotes the susceptibility value, R and W are ratings and weights of the caused factors, respectively, n is the number of factors.

4. Results

4.1 Assessment of individual geological-hazard susceptibility

According to above analysis, aforementioned causal factors of each geo-hazards are considered as assessment indexes of individual geo-hazards susceptibility. And each index is standardized to a uniform rating scale and each of them is assigned a attribute value shown in Table 2. The weight of each index is assigned by applying AHP shown in Table 2, the consistency ratio (CR) of all judgment matrix is less than 0.1, which indicates that the comparison matrix is consistent.

<Table 2>

According to an established classification criteria of evaluation indexes for geological hazards susceptibility shown in table 2, the susceptibility value was calculated by using Eq.(3). Based on the equidistant division method, the susceptibility value is divided into four classes: lowest, low, high, and highest. Based on classification of the susceptibility value, and the study area is classified into four geo-hazard susceptibility areas accordingly. The susceptibility map of individual geo-hazards is produced within MapGIS 6.7 environment. First, the basic data of the study area are converted to raster images of each factor using the image processing in MapGIS 6.7. Next, the images are reclassified and assigned the corresponding value of each rank using graphics processing. Finally, the susceptibility map is produced by weighted overlying ranking maps with the spatial analyst tool of MapGIS 6.7. The susceptibility map of individual geo-hazard is shown in Fig. 08-Fig.12.

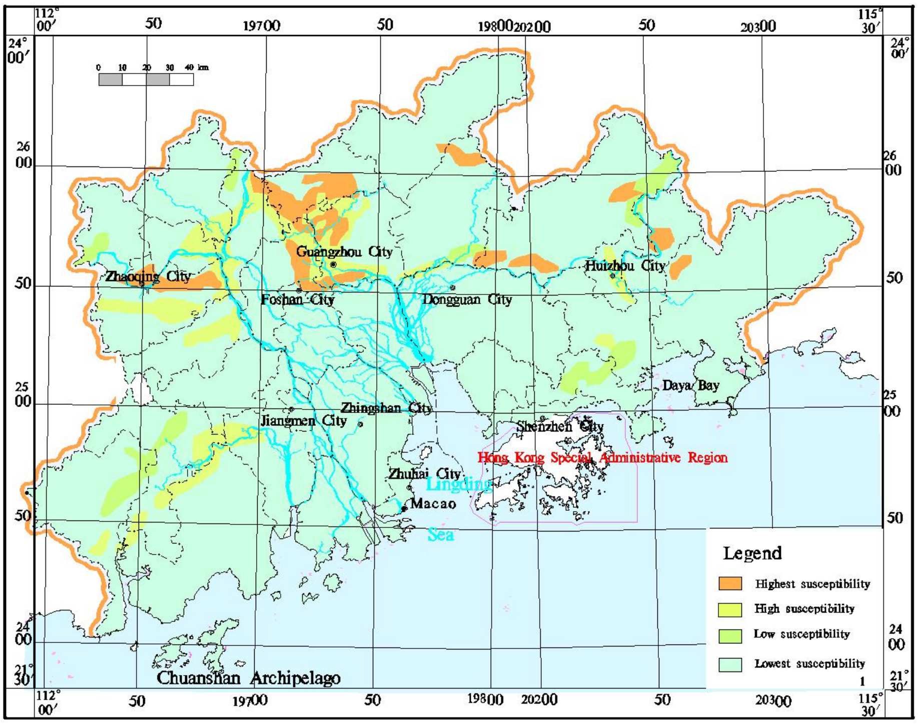

Fig.08 Karst collapse susceptibility map of the study area

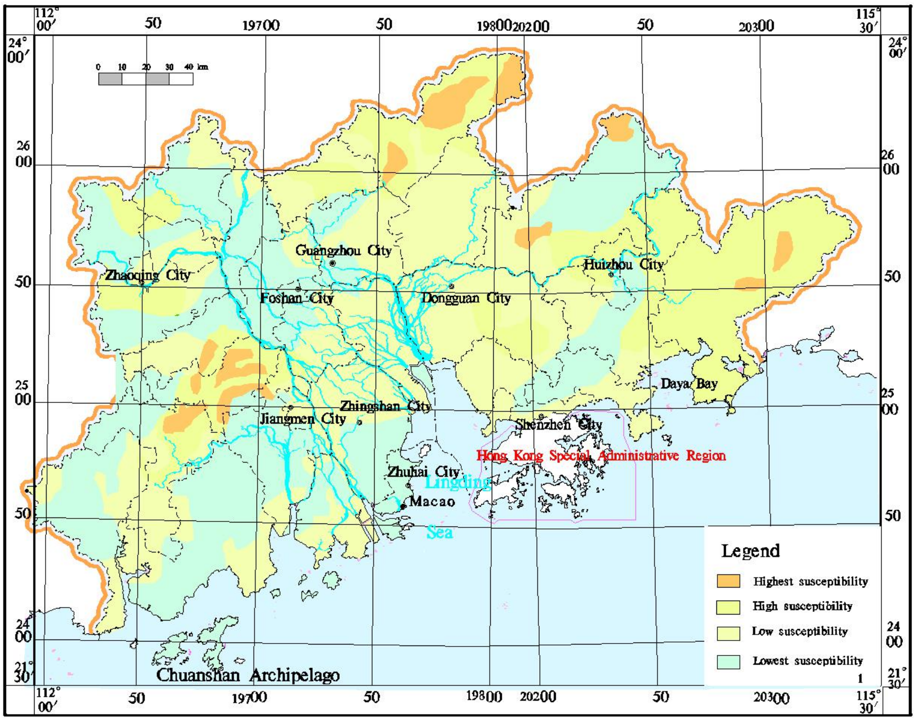

Fig.09 Collapse and landslides susceptibility map of the study area

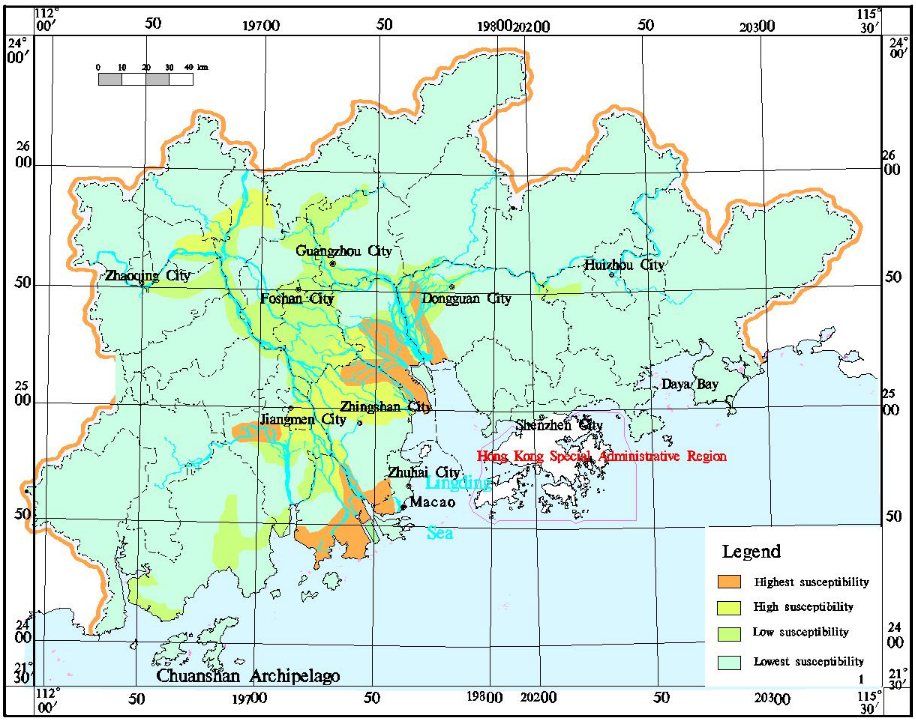

Fig.10 Ground subsidence susceptibility map of the study area

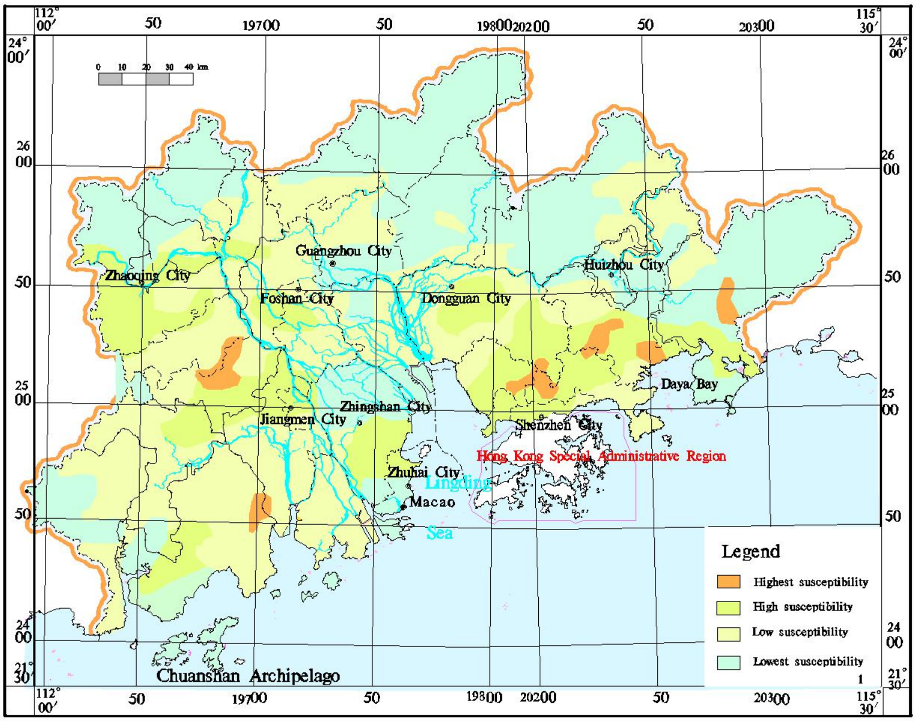

Fig.11 Water and soil erosion susceptibility map of the study area

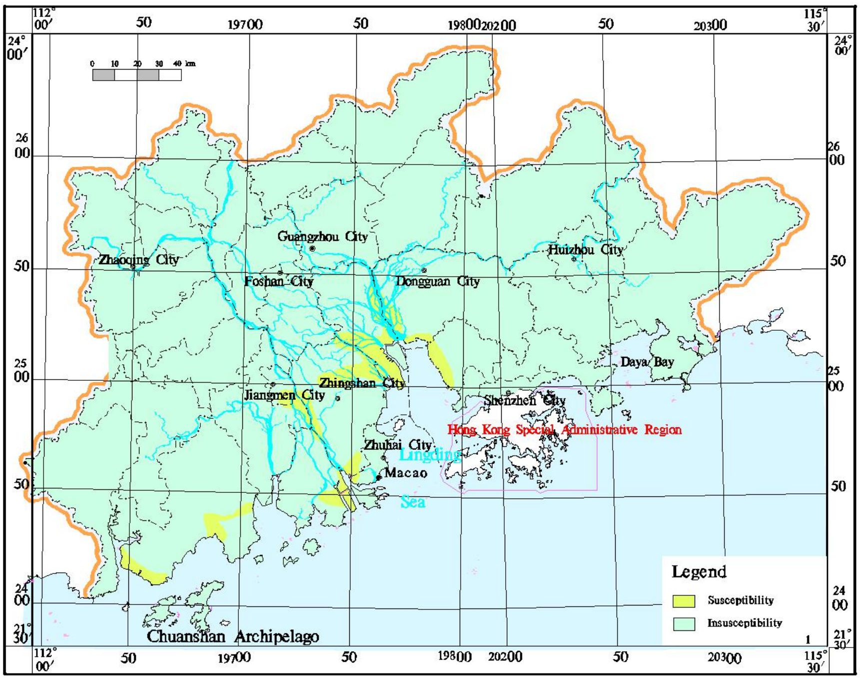

Fig.12 Seawater intrusion susceptibility map of the study area

4.2 Assessment of multi-hazards susceptibility

Based on the result of individual geo-hazard susceptibility, the multi-hazard susceptibility is evaluated by using the Difference Method. Moreover, the multi-hazard susceptibility map for the study area is produced by synthesizing five geo-hazard susceptibility maps in the MAPGIS 6.7 platform, and this map was further reclassified into four classes: high susceptibility, medium susceptibility, low susceptibility and insusceptible (Fig.13).

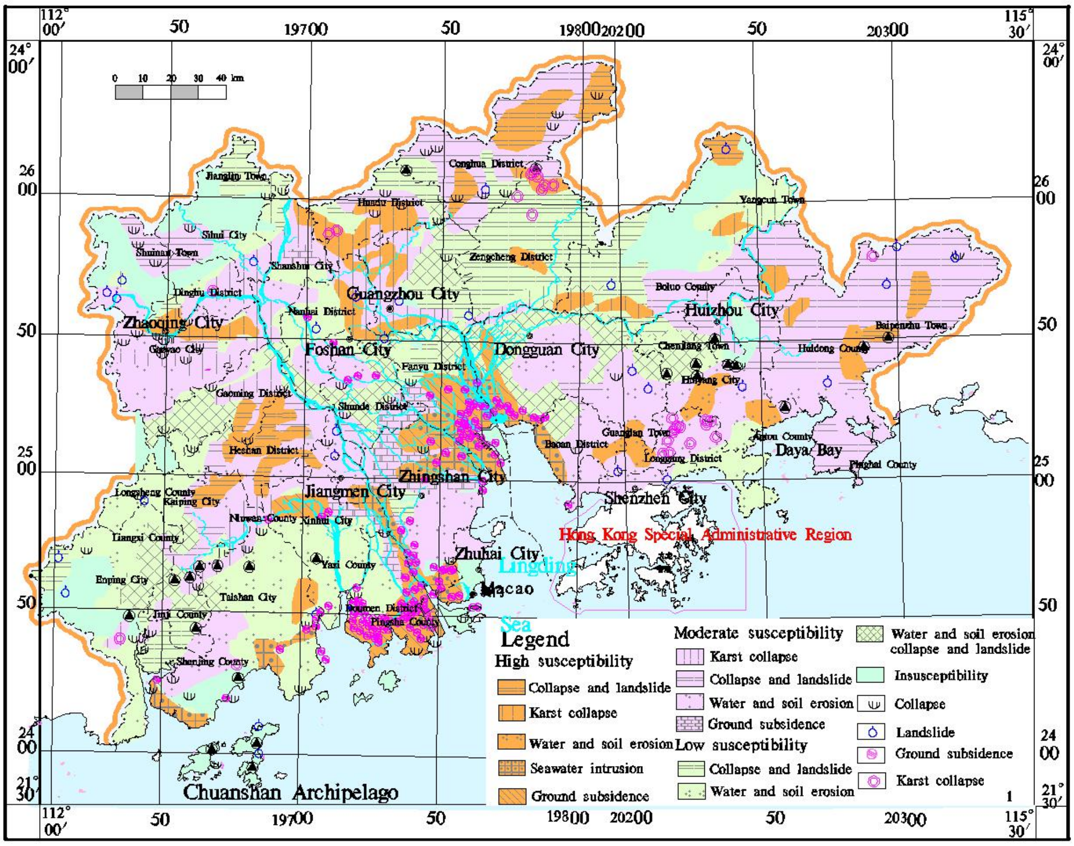

Fig.13 Comprehensive susceptibility map of geological hazards

4.2.1 High susceptibility zones

(1) High susceptibility zone of collapses and landslides

This zone is mainly located in the north of Conghua District, Heshan City, the northern border area of Boluo County and Baipenzhu Town. The zone is mainly distributed in low mountains and hilly area, which is characterized as steep terrain and high elevation. The outcropped lithology consists of intrusive rocks and metamorphic rocks, and metamorphic rocks is characterized as wide distribution, large thickness, and strong erosion and denudation. Human activities such as slope excavation contributes to cause the slope instability under adverse geological conditions. The climate is complex, with high annual precipitation, and rainfall is major factor to trigger geological hazards.

(2) High susceptibility zone of karst collapse

This zone is mainly located in Huadu District and Nanhai District of Guangzhou City and Zhaoqing City, few areas of this zone are distributed in Boluo County, Huizhou City and Huidong County. The terrain is relatively flat. This zone is located in karst areas, so it has the basic conditions for occurrence of karst collapse. So much infrastructure and large-scale construction projects are built in this zone, and intensity of human engineering activities is large. Due to much exploiting of groundwater in the construction of underground engineering, the original balance of rock and soil mechanics is artificially changed, which is prone to ground subsidence. The change of groundwater table is critical factor to trigger geological hazards in this zone.

(3) High susceptibility zone of water and soil erosion

This zone is mainly distributed in Guanlan Town, Huiyang District, Heshan City and the eastern area of Taishan City. The engineering geological conditions are complex, the soil is characterized by loose structure, poor soil viscosity and high erodibility, especially in Longgang District and Huiyang District, where natural soil erosion is intense, and the soil are deeply cut by river. High precipitation, especially heavy rain and intense rainstorm in the summer, destroys the original vegetation and slope conditions, and has strong erosion and scour on soil.

(4) High susceptibility zone of seawater intrusion

This zone is mainly distributed in Zhongshan City, Jiangmen City, Nansha District and Doumen District. This zone is located in delta plain area. A large area of saline water is formed in this zone, where the salinity of groundwater is high, and seawater intrusion occurred in part areas. Due to much exploiting of groundwater in the construction of underground engineering and small annual precipitation, groundwater cannot be recharged in time, causing lowing of groundwater table which is primary reason for seawater intrusion to occur in this zone. Moreover, this zone is susceptible to occur ground subsidence, due to widely distributed mollisol, and high water content and compressibility of mollisol.

(5) High susceptibility zone of ground subsidence

This zone is mainly distributed in Fanyu District and Niuwan Town and Pingsha Town. This zone is located in delta plain area. The outcropped lithology is mainly sandstone group. The Quaternary sedimentary mollisol characterized as a multi-layer structure, large thickness and wide distribution is affected by self-weight, resulting in self-weight consolidation. So it is prone to ground subsidence.

4.2.2 Moderate susceptibility zones

(1) Moderate susceptibility zone of collapses and landslides

This zone is mainly distributed in Conghua District, Nanshui Town, Kaiping City and the northern area of the study area. This zone is dominated by low mountains and high hills. The lithology mainly consists of intrusive rocks, volcaniclastic rocks and metamorphic rocks, with strong erosion. The annual precipitation is high. The rainfall is the major triggering factor for the occurrence of collapse and landslide.

(2) Moderate susceptibility zone of water and soil erosion

This zone is mainly distributed in Gaoyao City, Zhaoqing City, Shenjing Town, Heshan City, Jiangmen City, Zhongshan City area, Dongguan City, Longgang District and Huiyang District. This zone is mainly dominated by low mountains, hills and platform. The soil is mostly loamy clay, which is prone to surface loss under lessivage of clay particles. The outcropped lithology mainly consists of intruded rocks, volcanic rocks, and layered clastic rocks with carbonate rocks group. The rainfall has strong erosion and scour on soil. The vegetation coverage is small. The cultivated land is distributed in the Pearl River Delta coast area, and frequent tillage is more likely to cause water and soil erosion. The occurrence of water and soil erosion is mainly triggered by human factors.

(3) Moderate susceptibility zone of water and soil erosion

This zone is mainly distributed in Shunde District, the northwest area of Zhongshan City, the eastern area of Doumen District and the central area of Sanshui District. This zone is located in delta plain area. The outcropped lithology is mainly sandstone group. The mollisol with a multi-layer structure is widely distributed in this zone, and the thickness of mollisol range from 5 m to 20 m. Much exploiting of groundwater causes lowing of groundwater table, resulting in form of depression cone in exploiting region, which causing compression and consolidation of Quaternary sand layer. The original balance of rock and soil mechanics is artificially changed under human engineering activities, causing ground subsidence.

(4) Moderate susceptibility zone of karst collapse

This zone is mainly distributed in Dinghu District, the adjacent area between Sihui City and Shanshui District, Guangdong City, Kaiping City and the northwest marginal area of Taishan City. This zone is dominated by the delta plain and platform, characterized by flat terrain and low ground elevation. Engineering geological conditions is complex, the lithology consists of clastic rock group, red clastic rock group, and volcanic intrusive rock, with strong erosion. The karst is distributed in parts area of this zone. Much exploiting of groundwater and mining causes the change of groundwater table, which is major reason to trigger karst collapse.

4.2.3 Low susceptibility zones

(1) Low susceptibility zone of collapses and landslides

This zone is mainly distributed in Conghua District, Boluo County, Jianglin Town, Fanyu District and Jinji Town. This zone is dominated by low mountains and hills, and ground elevation is less than 100 m. The outcropped lithology is composed of intrusive rocks and metamorphic rocks. The engineering geological condition is simple. The annual precipitation is less than annual precipitation for the entire study area. Thus, it is not prone to collapse and landslide.

(2) Low susceptibility zone of water and soil erosion

This zone is mainly distributed in Liangxi Town, Longsheng Town, Taishan City, Yaxi Town, Doumen District, Foshan City and Yangcun Town. This zone is dominated by low mountains and hills. The outcropped lithology consists of sandstone group and intrusive rocks. This zone is characterized by weak soil erosion, small river system and large vegetation coverage. Water and soil erosion occurred in few areas of this zone and is caused by human activities.

(3) Low susceptibility zone of geological hazards

This zone is not prone to collapse, landslide, karst collapses and water and soil erosion. This zone is mainly distributed in Foshan City, the northern area of Dongguan City, Chenjiang Town, the northern area of Shunde District, and Gaoming District. The topography consists of low mountains, hills, platform and delta plain. This zone is characterized by small slope and developed geological structure. But human engineering activities are weak and precipitation is small. Thus, it is not prone to trigger geological hazards.

4.2.3 Insusceptible zone of geological hazards

This zone is mainly distributed in the northwest area of the study area, Enping City, Shalan Town and Boluo County, it extends for 107 km^2, accounting for 8.1% of the study area. This zone is located in hilly area. The outcropped lithology consists of metamorphic rocks and intrusive rocks. This zone is characterized by small population density, large vegetation coverage and weak intensity of human activities, which has weak destruction on geological environment. Moreover, few geological hazards are found in this zone and hazards events keep away from residential areas, which has a weaker threat to the life and property of local residents.

5 Analysis of the causes of geo-hazards

5.1 Composition conditions

Topography. The geological hazards that are greatly affected by topography are collapse and landslide within the study area. In the study area, the collapse and landslide are founded in low mountains and hilly area, karst collapses occur in the karst development area, water and soil erosion occur in hilly area and platform, and it mostly occur in the slope with 15° - 30° .

Stratigraphic lithology. The study area is widely distributed with loose alluvial-diluvial layer, eluvium layer, swell-shrinkage soil and colluvial soil, loose rocks is characterized by weak lithology and low shear strength. So it is susceptible to collapse, landslide and other geo-hazards under influence of triggering factors. Karst is more developed, so it is prone to karst collapse under the affect of human activity. The mollisol is characterized by high water content, high compressibility, low shear strength and low bearing capacity, so it is prone to ground subsidence and mollisol foundation subsidence. Weathering residual soil has poor corrosion resistance, and it is easy to collapse in case of water, so it is prone to water and soil erosion.

Geologic structure. It is susceptible to cause collapses in some area, characterized by strong tectonic movement, broken stratum and frequent earthquake.

5.2 triggering factors

(1) Precipitation

There are more geological hazards can be found in some areas with large precipitation. In areas with large annual precipitation, the surface runoff is very strong and the slope toe are deeply cut by the rivers resulting in formation of temporary surface. The precipitation can increase pressure of pore water in soil body and reduce the shear strength of soil body, result that the slope is prone easily destabilized and destructed. The rainfall for the study area is abundant and has a unevenly temporal distribution. The raindrop has strong the scouring effect and erosion on ground during rainfall, resulting in water and soil erosion. Table 3 shows the quarterly distribution characteristics of collapses during the recent 15 years within the typical area of the study area. From table 3, it is indicated that collapses primarily occurred in the rainy season from June to September, and it maintains consistency with the distribution of monthly precipitation.

<Table 3>

(2) Human activities

Unreasonable human activities are important factors for causing frequent occurrence of geological hazards such as collapses, landslides, ground subsidence, ground collapse and so on. In the study area, slope cutting effect under demand of building houses and road construction have a major impact on the formation of geological hazard. Human activities such as excavating the slope toe and cutting slope can change the stress state of the original balance of mountain slope and destroy vegetation of the slope, so it is easily trigger collapses and landslides. Large-scale high-rise building construction, exploitation of underground space and other major projects applied static load on foundation, which can change the stress balance of engineering foundation and make the soil body of foundation creep, and it cause the compaction and deformation of soil body. Finally, it will trigger ground collapse and ground subsidence.

Over-pumping groundwater is primary factor to cause karst collapse and ground subsidence.

6 Validation of the results

Sensitivity analysis is used to assess effects of the input criteria on the model output performance and also to validate the effect of changing variable conditions or parameter values on the system (Gomez and Jones 2010). Sensitivity analysis is to determine the effective weight of each parameter and compare it with the theoretical weight for verifying the information on the effect of scaled values and weights assigned to each parameter. The effective weight, called coefficient of variation, is computed using the following Eq. (4) (Napolitano and Fabbri 1996).

$$W = \frac{P_r \cdot P_W}{V} \cdot 100 \quad (4)$$

where W is the effective weight of the parameter P, Pr and Pw are the scaled value and the weight of the parameter P, respectively, and V is the susceptibility index of geo-hazard.

The result of individual geo-hazard susceptibility assessment (e.g. collapse and landslide, Karst collapse, ground subsidence, water and soil erosion and seawater intrusion) is verified by sensitivity analysis. The sensitivity analysis result is shown in

Table 4. Table 4 represents the effective weights with the theoretical weight for individual geo-hazard susceptibility criterion. The effective weights of each parameters are slightly different from the theoretical weight assigned to individual geo-hazard susceptibility, which validates the accuracy and rationality of the assessment method.

<Table 4>

7 Conclusions

The aim of this study is to assess multi-hazard susceptibility and identify different susceptibility area in the Pearl River Delta Economic Zone, where various hazards occurred. This paper presents a first attempt to propose an new method that integrated the Analytic Hierarchy Process (AHP) and the Difference Method (DM) to assess multi-hazard susceptility. Based on the geo-hazards investigation and local geological environmental conditions, this paper systematically analyzes the occurrence mechanism and formation conditions of geological hazards and summarizes the causal factors for controlling occurrence of geological hazards. And based on the above analysis process, individual geo-hazard susceptibility is assessed by applying the Analytic Hierarchy Process (AHP) and MapGIS technology. The multi-hazard susceptibility is assessed by the Difference Method (DM) based on above individual geo-hazard susceptibility result, and the assessment results are plotted in a multi-hazard susceptibility map on MapGIS 6.7 platform.

The multi-hazard susceptibility map shows most of areas of the study area are under the middle and low susceptibility zones, accounting for 75.2% of the total study area. High susceptibility zone covers an area of 6662.24 km^2, accounting for 16.5% of the study area, where geo-hazards are likely to occur due to poor geological environment and strong human activities. Moderate susceptibility zone covers an area of 16806.91 km^2, accounting for 41.6% of the entire study area, remaining area are under low susceptibility zone and insusceptible zone, accounting for 41.9% of the entire study area. The geo-hazards susceptibility maps is verified by sensitivity analysis, the sensitivity analysis result verifies accuracy of new method and indicates that this new method suits the study area. This study can provide theoretical guide to urban planning and geo-hazards prevention for achieving the optimal allocation of geological resources and environment, and it can be combined with present land use map to provide scientific basis to adjust land use planning, coming true the rational use of land resources.

References:

Bijukchhen, S. M., Kayastha, P. and Dhital, M. R.: A comparative evaluation of heuristic and bivariate statistical modelling for landslide susceptibility mappings in Ghurmi-Dhad Khola, east Nepal. Arab J Geosci, 6(8), 2727–2743, 2013.

Cui, A. P.: Application of Information System Spatial Analysis and Attacking Coefficient Method to the Classification of Geological hazards in Lueyang County, Journal of Catastrophology, (02), 53-57, 2004 [in Chinese].

Degg, M.: Natural hazards: Recent trends and future prospects, Geography, 198-209, 1992.

Deng, X. Y. and Yi, S. M.: Space-Time Distribution Characteristics of Rockfall Hazard Activities in Guangdong, Chinese Journal of Engineering Geophysics, 5(3), 356-363, 2008 (in Chinese).

Fu, Y. C., Wu, S. T., Zhang, Q. and Shi, L.: The susyitution of the carst forecasting and evaluating methods based on the GIS, Geology of Chemical Minerals, 31(4), 227-231, 2009 (in Chinese).

Gomez, B., Jones, P. J.: Research methods in geography-a critical introduction. Wiley, Chichester, 2010.

Karaman, H.: Integrated multi-hazard mapcreation by using AHP and GIS, 7th International Conference on Natural Hazards (NAHA '15), 40, 101-110, 2015.

Karaman, H. and Erden, T.: Net earthquake hazard and elements at risk (NEaR) map creation for city of Istanbul via spatial multi-criteria decision analysis, Nat. Hazards, 73 (2), 685 – 709, 2014.

Komac, M.: A landslide susceptibility model using the analytical hierarchy process method and multivariate statistics in perialpine Slovenia, Geomorphology, 74(1), 17 – 28, 2006.

Lee, C. Fang., Huang, W. K., Chang, Y. L., Chi, S. Y. and Liao, W. C.: Regional landslide susceptibility assessment using multi-stage remote sensing data along the coastal range highway in northeastern Taiwan, Geomorphology, 300, 113-127, 2018.

Li, J. X.: Study on the relationship between geological hazards and geological environment in Guangdong Province, West-China Exploration Engineering, (8), 111-113+117, 2012.

Liu, D. J.: The situation and analysis of salinity intrusion in coastal areas, China, Journal of Geological Hazards and Environment Preservation, 15(1), 31-36, 2014.

Li, B. Y., Li, J. Z. and Wang, J. J.: Areal association of natual hazard in China, Acta Geocraphica Sinica, 51(1), 1-2, 1996 (in Chinese).

Liang, S. Y., Wang, Y. X. and Wang, Y.: Risk assessment of geological hazard in Wudu area of Longnan City, China. Applied Mechanics and Materials; 39, 232-237, DOI:10.4028/www.scientific.net/AMM.39.232, 2011.

National Disaster Mitigation Center Disaster Information Department.: The characteristic features of natural disasters in China, Disaster Reduct China, 1, 10-11, 2009.

Napolitano, P., Fabbri, A. G.: Single-parameter sensitivity analysis for aquifer vulnerability assessment using DRASTIC and SINTACS. In: Proceedings of the Vienna conference on HydroGIS 96: application of geographic information systems in hydrology and water resources management, IAHS Pub. 235, 559-566, 1996.

Peng, S. H., Shieh, M. J. and Fan, S.Y.: Potential hazard map for disaster prevention using GIS-based linear combination approach and analytic hierarchy method. J. Geogr. Inf. Syst, 4, 403 – 411, 2012.

Pradhan, A. M. S. and Kim, Y. T.: Evaluation of a combined spatial multi-criteria evaluation model and deterministic model for landslide susceptibility mapping, Catena, 140: 125–139, 2016.

Rozos, D., Bathrellos, G. D. and Skilodimou, H. D.: Comparison of the implementation of rock engineering system (RES) and analytic hierarchy process (AHP) methods, based on landslide susceptibility maps, compiled in GIS environment. A case study from the eastern Achaia County of Peloponnesus, Greece, Environ. Earth Sci, 63 (1), 49 – 63, 2011.

Saaty, T. L.: Decision making with the analytic hierarchy process, International Journal of Services Sciences, 1(1), 83-98, 2008.

Saaty, T. L.: The analytic hierarchy process: planning, priority setting, resource allocation. New York, USA: McGraw-Hill, 2008.

Su, W. C.: Karst collapse hazards research and prevention in major cities of Guizhou Province, Hydrogeology Engineering Geology, 25(3), 40-42, 1998 (in Chinese).

Tang, B. X. and Wu, J. S: Mountain natural hazards dominated (mainly debris flow) and their prevention, Journal of Geographical Sciences, (2), 202 – 209, 1990 (in Chinese).

Sun, Z. X., Chen, J., Xie, Q. and Long, A. M.: Status Quo of Seawater Intrusion in

Western Coastal Area of Pearl River Estuary, Survey and Diagnosis. Environmental Science & Technology, 34(8), 81-84, 2011 (in Chinese).

UN.: Johannsburg plan of implementation of the world summit on sustainable development, Technical report, United Nations, 2002.

Uitto, J. I. and Shaw, R.: Sustainable development and disaster risk reduction: Introduction. In: Sustainable Development and Disaster Risk Reduction. Springer Japan, 1–12, 2016.

Wang, B., He, K. Q. and Gao, Z. J.: Temporal and Spatial Analysis of Karst Collapse Development, Hydrogeology Engineering Geology, 28(5), 24-27, 2001 (in Chinese).

Wang, N. T., Shi, T. T., Ke, P., Wei, Zhang. and Jin, X. W.: Assessment of geohazard susceptibility based on RS and GIS analysis in Jianshi County of the Three Gorges Reservoir, China, Arab J Geosci, 8, 67-86, DOI 10.1007/s12517-013-1196-7, 2015.

Wang, L., Guo, M., Sawada, K. et al.: Landslide susceptibility mapping in Mizunami City, Japan: A comparison between logistic regression, bivariate statistical analysis and multivariate adaptive regression spline models, Catena, 135, 271－282, 2015.

Yilmaz, I.: Landslide susceptibility mapping using frequency ratio, logistic regression, artificial neural networks and their comparison: a case study from Kat landslides (Tokat - Turkey), Computers & Geosciences, 35(6), 1125-1138, 2009.

Zhou, J. X., Wang, L. X., Xie, B. Y. et al.: A study on the early-warning technique concerning debris flow hazards, Journal of Geographical Sciences, 12(3), 363-370, 2002.

Zhang, W.: Space distribution regularity of geo-hazards in Guangdong province, Journal of Green Science and Technology, 7, 221-223, 2012 (in Chinese).

Table 1 Value of RI

Order n	1	2	3	4	5	6	7	8	9
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45

Table 2

Assessment factor system of geological hazards susceptibility

Criterion layer	Evaluation index	The score and rank of assessment indexes 1	2	3	4	Weight
Karst collapse	Degree of karst development	Strong	Moderate	Poor	—	0.2100
	Overburden thickness (m)	＜10	10-30	>30	—	0.3211
	Lithology	Limestone,dolomite	Glutenite,mud limestone,tuff, sandstone	Clay rock, mudstone, shale, silty sandstone, silty slate	—	0.2100
	Aquifer water yield property	Weak	Moderate	rich	—	0.1001
	The distance to the fracture	0-2000	2000-4000	>4000	—	0.1587
Collapse and landslide	Topography	Delta plain,marine deposition terrace	Alluvial plains, alluvial and diluvial plains, alluvial and marine deposition plains	Hilly area	Low mountainous area	0.3300
	Lithology	Pluton, shale	Medium - thick layered carbonate rocks,	layered metamorphc, rock	layered clastic rocks	0.3300
	The distance to faults	＜1000	1000-2000	2000-3000	＞3000	0.1996
	Precipitation	＜1600	1600-1800	1800-2000	＞2000	0.1404
Ground subsidence	The thickness of millisol	＜10	10～20	>20	—	0.4249
	Aquifer water yield property	Weak	Moderate	Rich	—	0.2701
	The deposition age of millisol	Holoce nemarine deposit - sea alluvial Guizhou group, the upper Pleistocene middle	Holocene alluvia Dawan Town group - the middle Holocene lake marsh Mugao group	Holocene alluvial group, red bed residual soil	—	0.1613
	The distance to the fracture	＜2000	2000-4000	>4000	—	0.1438
Water and soil erosion	Topography	Delta plain,marine deposition terrace	Alluvial Plains, alluvial and diluvial plains, alluvial and marine deposition plains	Hilly area	Low mountainous area	0.2140
	Vegetation type	Arbor,shrub	Economic forest, shelterbelt,	Crops	Construction land Unused land	0.2499
	Soil type	Paddy soil	Red loam	Fluvo-aquic soil	Latosolic red soil	0.3079
	Precipitation	<1800	1800-2000	2000-2200	>2200	0.1191
	the density of of river	Scattered	More scattered	Even	Concentrated	0.1092

	network					
Seawater intrusion	Topography	Delta plain, marine deposition terrace	Alluvial plains, alluvial and diluvial plains	hilly area	Low mountainous area	0.1438
	The type of Quaternary sedimentary rock	Bedrock	Holocene lacustrine sediment colluvium	Holocene marine clay	Holocene sea alluvial clay	0.1613
	Groundwater table	<0	0-10	10-60	>60	0.2701
	Precipitation	<1800	1800-2000	2000-2200	>2200	0.4248

Table 3

The quarterly distribution characteristics of collapses in the study area between 1990 and 2006

Time	Jan - March		Apr - Jun		July - Sep		Oct - Dec	
City	Number	Percentage	Number	Percentage	Number	Percentage	Number	Percentage
Zhaoqing City	13	6.88	51	26.98	97	51.32	28	14.82
Huizhou City	3	3.06	22	22.45	61	62.25	12	12.25
Guangzhou City	11	3.77	102	34.93	162	55.48	17	5.82
Shenzhen City	19	4.97	60	15.71	278	72.78	25	6.55

Table 4 Sensitivity analysis of individual geo-hazard susceptibility

Karst collpase			Collapse and landslide			Ground subsidence		
Parameters	Theoretical weight (%)	Effective weight (%)	Parameters	Theoretical weight (%)	Effective weight (%)	Parameters	Theoretical weight (%)	Effective weight (%)
Degree of karst development	21.0	24	Topography	33.0	30.6	The thickness of deposition	42.5	30.7
Overburden thickness	32.1	28.8	Lithology	33.0	30.0	Aquifer water yield property	27.0	29.1
Lithology	21.0	23.7	The distance to faults	20.0	20.8	The deposition age of millisol	16.1	20.3
Aquifer water yield property	10.0	8.7	Precipitation	14.0	19.6	The distance to the fracture	14.4	17.8
The distance to the fracture	15.9	16.7						

Water and soil erosion			Seawater intrusion		
Parameters	Theoretical weight (%)	Effective weight (%)	Parameters	Theoretical weight (%)	Effective weight (%)
Topography	21.4	22.5	Topography	14.4	14.9
Vegetation type	25.0	24.8	The type of Quaternary sedimentary rock	16.1	16.2
Soil type	30.8	29.6	Groundwater table	27.0	36.1
Precipitation	11.9	14.8	Precipitation	42.5	37.5
the density of of river network	10.9	10.7			