Land-use optimisation by geological hazard assessment in Nanjing City, China

FAMING ZHANG[1], QUANNING YANG[2], XUETIAN JIA[3], JIANDONG LIU[4] & BO WANG[5]

[1] *Geology Department of Hohai University. (e-mail: Famzhang@Tom.com)*
[2] *Jiangsu Geology Prospecting Bureau. (e-mail: Famzhang@Tom.com)*
[3] *Jiangsu Geology Prospecting Bureau. (e-mail: Famzhang@Tom.com)*
[4] *Jiangsu Geology Prospecting Bureau. (e-mail: Famzhang@Tom.com)*
[5] *Jiangsu Geology Prospecting Bureau. (e-mail: Famzhang@Tom.com)*

Abstract: Geo-hazards such as landslides, land subsidence, and ground collapses are significant problems in city planning. Based on an investigation of the geological hazards and the distribution of the geo-hazards in Nanjing City, China, a multi-scaled and systematic method to analyze the degree of risk was adopted. Land utilization in the development of Nanjing City was assessed by considering geological hazards using an Analytic Hierarchy Process. From this it was apparent that the land of Nanjing city could be divided up into 4 parts based upon the geological hazards: in the North of the city, the land is suitable for industrial usage; in the south, the land is suitable for human habitation; the bank of the Yangzhi River is suitable for port construction and parking; and the fourth part of the city is suitable for storehouse, commerce and other uses.

Résumé: Les Geo-risques tels que des éboulements, l'affaissement de terre, et des effondrements de la terre sont les problèmes principaux dans la planification de ville. Basé sur une recherche sur géologique les risques et la distribution des geo-risques dans la ville de Nanjing, la Chine, une méthode muti-mesurée et systématique pour analyser le degré de risque a été adoptée. La terre optimisent l'utilisation dans le développement de la ville de Nanjing a été évaluée en considérant les risques géologiques en utilisant un processus analytique de hiérarchie. De ceci il était évident que la terre de la ville de Nanjing pourrait être divisée en 4 parts selon les risques géologiques: dans le nord de la ville, la terre convient à la construction d'industrie; dans le sud, la terre convient à la vie humaine; la banque du fleuve de Yangzhi convient à la construction et au stationnement gauches; et la quatrième partie de la ville convient à l'entrep?t, au commerce et à d'autres utilisations. La méthode géologique d'évaluation de risques est présentée dans cet article, et les résultats de la recherche qui ont été employés dans la planification de ville.

Keywords: geological hazards; risk assessment; land use; numerical models

INTRODUCTION

Nanjing is a famous ancient city in Yangzhi river downstream delta area, situated in the east of China. The population of Nanjing city is ~5 million. Since 1970, the city has developed rapidly and underground construction has become significant. Geological hazards are common. According to government planning, the total area of Nanjing city will be 6516 km^2. Given this fact, it is necessary to assess the land usage and natural hazards. As land development accelerates in the city and increased quantities of natural resources are extracted, it is important to understand the constraints on land use imposed by natural geological conditions, and to be aware of the damage to the total environment that may result from ignoring these constraints (Lokin 1990, Sterly & Godard 2002, Liu Yuhai, Chen Zhixib, Ni Wankui & Zhao Fasuo 1997, Dai, Lee & Zhang 2001, Sterling & Carmody. 1992, Duffaut 1982). In this study four types of land utilization are assessed using the Analytic Hierarchy Process and strengths, weaknesses, opportunities, and threats SWOT analysis method.

GEOLOGY OF NANJING

Topography and Physiognomy

Nanjing is situated on a river terrace of the Yangzhi River and the ancient river bed of the Qinghuai River runs through the city (Figure 1). To the north, east and south are mountains, while in the northwest is the Yangzhi River. In the north, along the Yangzhi River is the Mufu mountain (the elevation is 199~200 m) and Qixiao mountain (274 m), while in the east, is Zhijing mountain (448 m). Northwest of the city is the broad alluvial flat, the ground level is 70 m.

Tectonics background

Nanjing is situated in the adjacent area of Ningzhen arcuate structure and Ningwu basin. The geology is complicated, with a serious fold and fault structures. Generally, the bedrock depth of the city area is 20 to 40 m (Figure.2). Three exposed rock bed belts are distributed from north to south: Shizhisan—Mufusan mountain belt, Qingliangsan-Beijige belt and Yuhuatai—Juhuatai belt. Two basins are enclosed between the three bedrock belts. Faults are well developed in the city with the major tectonic strike being NWW, NW—NNW, NE and NNE. The four major faults called Gulou—Dinghuaimen fault, Gulou—Shizhisan fault, Jiuhuasan—Lahusan fault and Beijige faults. The bedrock is of the Sinian system and Cretaceous system composed of sediment or pyroclastic rock.

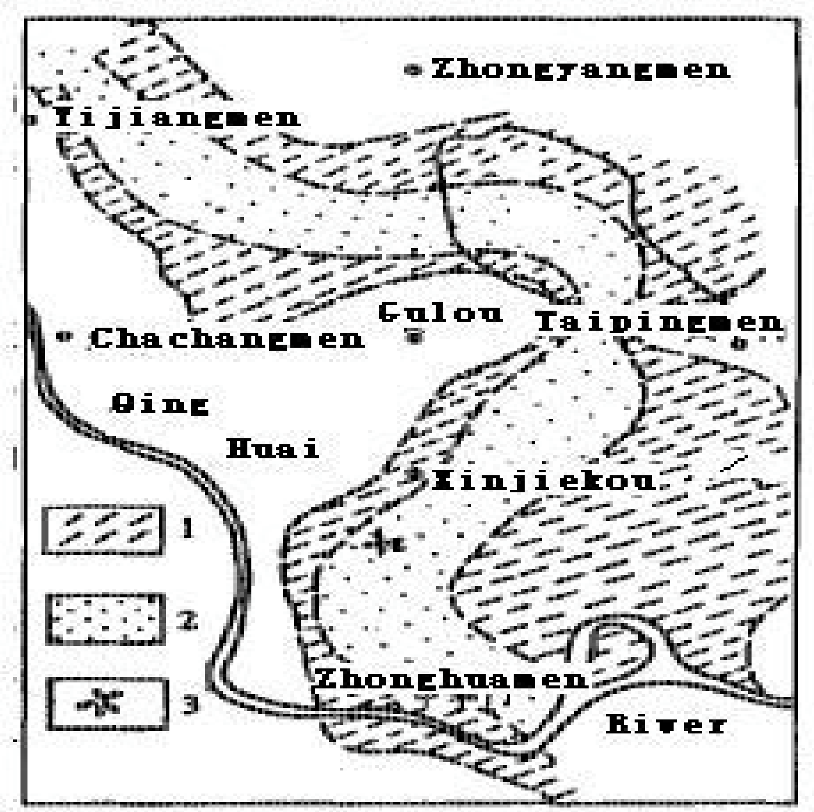

Figure 1. Sketch map of Qinghuai River ancient river channel
1--alluvial flat; 2—ancient river channel; 3—land collapse

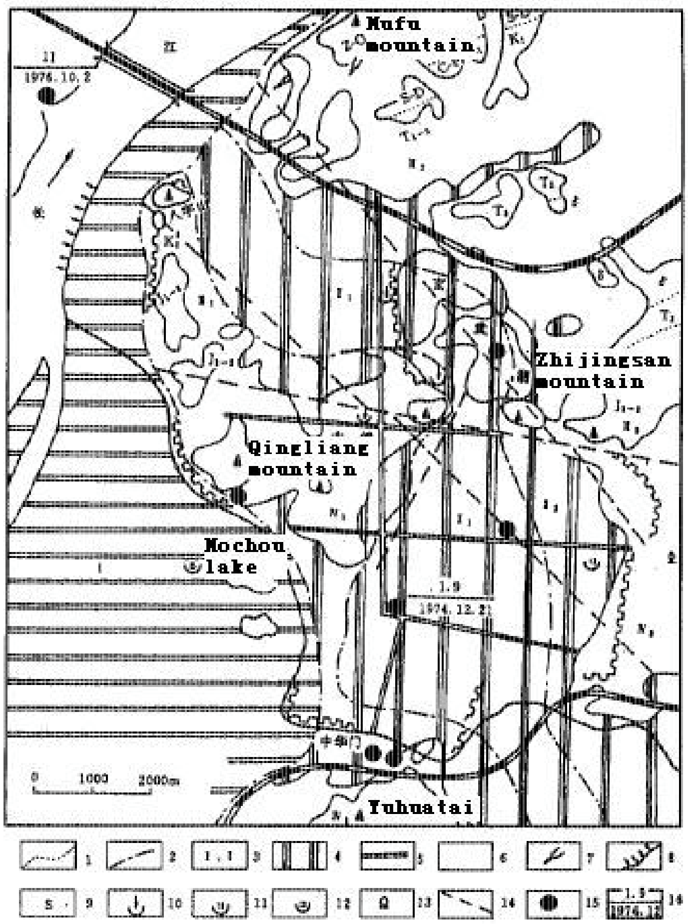

Figure 2. Geological zonation map of Nanjing city (Luo 2000)

Figure 3. Shizhisan mountain landslide (2003)

Figure 4. Photograph of the Huangsanling landslide taken in 2003.

GEOLOGICAL HAZARDS

Based conducting systematic city surveys of the geology of Nanjing city, the both the geo-resources and geo-hazards have been determined. Four types of geological hazards that occur in Nanjing city are discussed in greater detail.

Landslide

Landslides occur in Gulou, Yuhuatai and Qixiao districts of the city. Areas of major landsliding in Nanjing city are normally in the mountainous area, the largest having volumes ~ 1000 m^3, with the majority being <500 m^3. There are more than 100 landslides in Nanjing city distributed throughout the mountainous area. Most are superficial and are rainfall triggered. Figures 3 and 4 show landslides in Nanjing city.

Land subsidence and ground collapse

Land subsidence is a gradual settling or sudden sinking of the ground owing to subsurface movement of underlying materials. Subsidence is a major hazard in Nanjing city, and at present affects > 1 000 000 m^2 of the city. The principal causes are underground mining and groundwater withdrawal. In recent years, there have been 26 mining collapses in the Meisan iron ore, Tongjing goldmine, Jiuhuasan bronze mine, Guoli bronze mine and Anjisan bronze mine. The collapses have occurred down to 130 m. Collapse in karst is a consequence of extraction of underground water. The increasing development of land and water resources threatens to exacerbate existing land-subsidence problems and to initiate new ones. There are 28 Karst collapses distributed in Chalukou, Qixiao mountains and the Jiangnan cement plant area that affect a total area is about 2270 m^2. Figure 5 shows an example of collapse in the Meisan iron ore mine.

Figure 5. Collapse in Meisan iron ore mine

Bank collapse of Yangzhi River

Failures of the riverbanks of the Yangzhi River that runs through the city are common. The soft soils are prone to liquefaction and pose a problem for construction. In 1998, there were many bank failures occurred along the Yangzhi River in Nanjing city requiring slope stabilization strategies to be introduced.

EVALUATATION METHODS FOR LANDUSE

Land evaluation element division

Government city planners have divided the city in 6000 elements each 1×1 km^2 (Figure 6) containing information that can be queried in GIS such as geological characteristic, soil mechanics parameters, depth and thickness of the soft soil, groundwater table, and geology hazards.

Factors affecting land-use

Four kinds of the land-use are examined: industrial, commercial and domestic, landscape and storage. Table 1 shows the factors used to evaluate the geological environment for each of the four land uses.

Table 1. Geological factors influencing land-use

Geological environmental factors	Industrial	Commercial and domestic	Storage use of land	Landscape
Terrace ascent	*	*	†	†
Active faults and ground-fissure	*	*	‡	†
Buried depth of supporting layer	*	*	‡	‡
Bearing capacity of supporting layer	*	*	‡	‡
Collapse of foundation soil	*	*	‡	‡
Buried depth of groundwater	*	*	*	‡
Amount of groundwater	*	†	‡	‡
Material resources on earth surface	†	†	*	‡
Land subsidence	*	†	*	‡
Flood water calamity	*	*	*	*
Soil and water lose?	†	†	‡	‡

* strongly significant factors
† moderately significant factors
‡ less significant factors

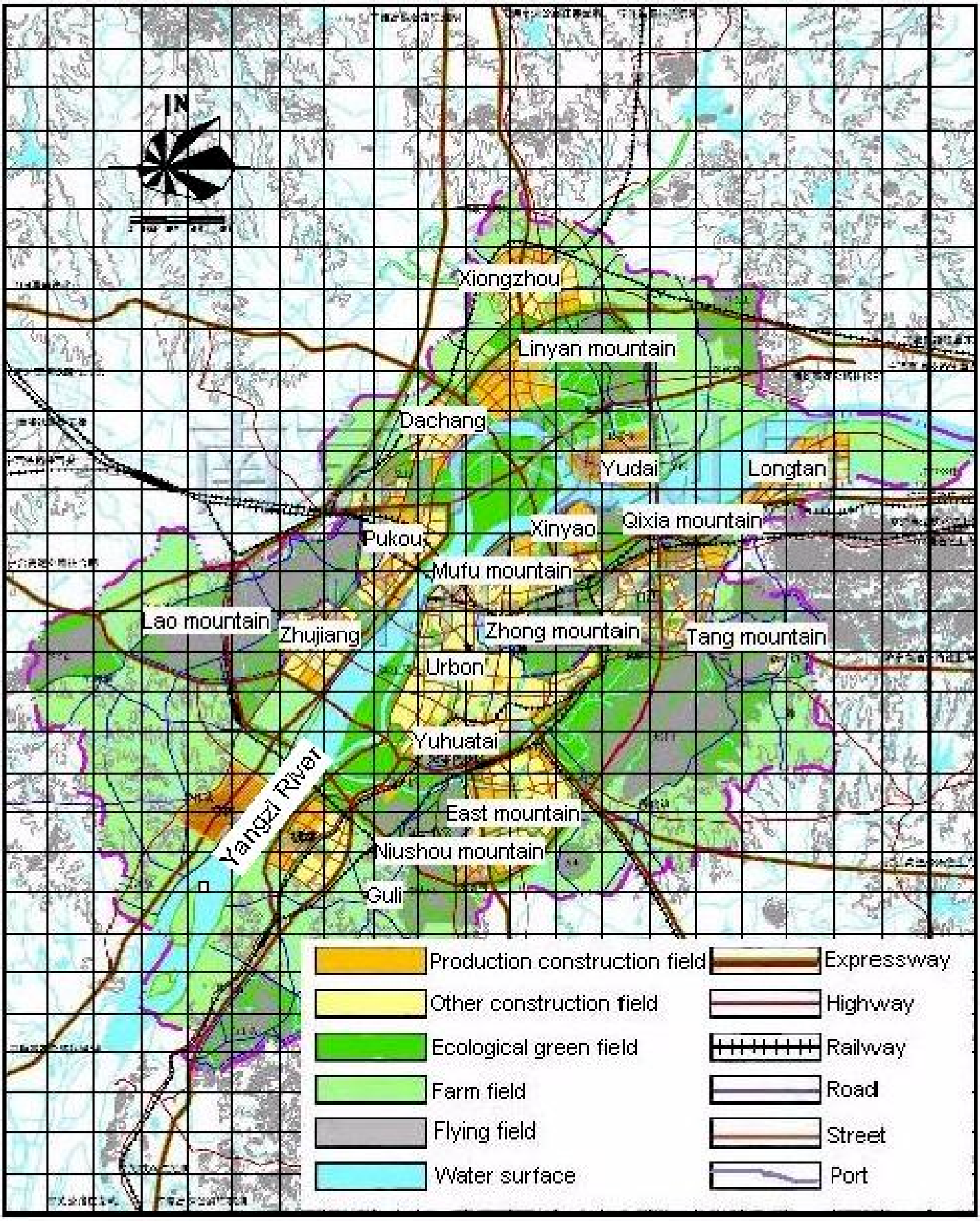

Figure 6. Evaluation area and element of Nanjing city.

In order to select the reasonable utilization of urban geological environmental in city development, it is necessary to optimize the geological factors for suitable land utilization of each land-use types. The relative significance of geological factors on the evaluation can be defined according to Table 2 using an Analytic Hierarchy Process method.

Analytic Hierarchy Process method in evaluation

Multi-criteria analysis (MCA) techniques are well-known decision support tools for dealing with complex decision constellations where technological, economical, ecological and social aspects have to be covered. The urban geological environment is a complicated system that has many factors that can affect different land utilization. Therefore, we use an Analytic Hierarchy Process Method (AHP) to evaluate the geological environment for different land uses (Sterling & Carmody 1992, Saaty 2003). The steps involved in the process are as follows:

Determine the evaluation factors

Different land uses require different geological conditions, for example, for human habitation there is a need for site transportation, facilities, firm foundation conditions, moderate to low angled slopes, no active faults or ground fissures The factors considered in evaluation of 4 types of land-use is shown in Table 1.

Determine the weights of different factors in evaluation

Having determined the evaluation factors, the next step is to give a weight to each factor through which its relative significance upon land-use can be assessed. However, assigning weights quickly becomes a difficult task as the number of factors considered increases. The AHP as a multi-objective multi-criteria decision-making approach that uses a pair wise criteria comparison to arrive at a scale of preferences among sets of alternatives (Saaty & Vargas 1991). Experts making decisions of the weighting value need to decide which is more significant between Di and Dj according to the criterion Ck. It can adopt the scale of 1 to 9 and grant a certain number according to its relative significance (Table 2). For example, if there are 7 factors D21, to D27 that affect land-use (Figure 6), the weight can be determined as in Table 3 by using AHP method.

Table 2. The scale of judging matrix and the meaning (Saaty & Vargas 1991)

The scale	Meaning
1	When comparing two factors, they have the same significance
3	When comparing two factors, Moderate importance of one factor over another
5	When comparing two factors, one is obviously more significant than the other
7	When comparing two factors, one is very strong importance than the other
9	When comparing two factors, one is dreadfully more significant than the other
2,4,6,8	Intermediate value
Reciprocal	We can get judge b_{ij} according to the comparison between factor i and j, then the judge b_{ji} of comparison between j and i equal to $\frac{1}{b_{ji}}$

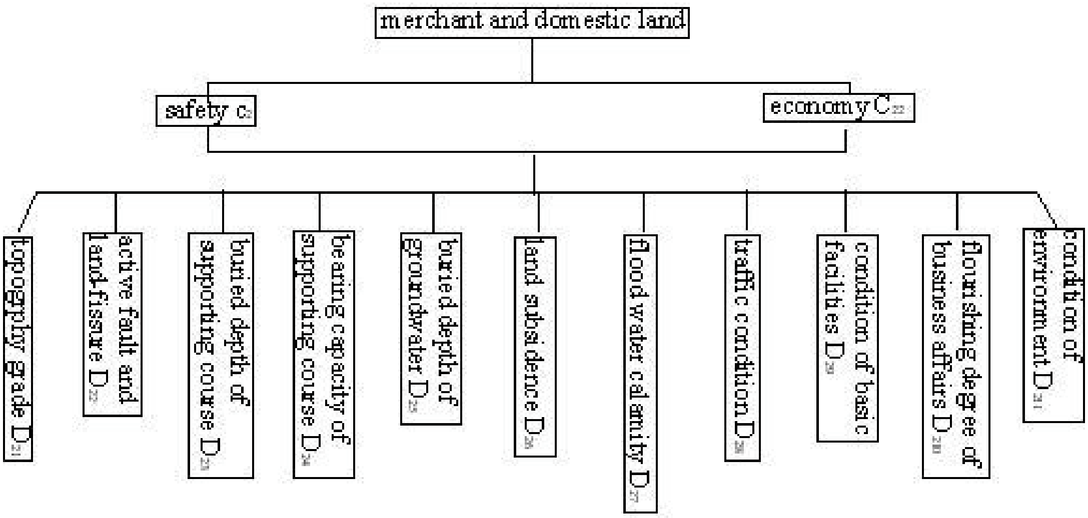

Figure 6. Analytic model of suitable hierarchy structure of merchant and domestic used land

Table 3. Weighting value and criterion matrix of factors

C21	D21	D22	D23	D24	D25	D26	D27	W
D21	1	1/5	1/3	1/5	1/3	1/2	1/4	0.030
D22	5	1	5	4	5	5	3	0.301
D23	3	1/5	1	1/3	3	3	1/4	0.116
D24	5	1/4	3	1	5	5	2	0.228
D25	3	1/5	1/3	1/5	1	1/2	1/4	0.059
D26	2	1/5	1/3	1/5	2	1	1/5	0.064
D27	4	1/3	4	1/2	4	5	1	0.202

Calculation of evaluation value

By using an AHP method, relative weight W can be calculated and the total evaluation value of each factor as arrived upon using the following formula. As an example, the criterion of geological environment of commerce and domestic land utilization was shown in Table 4.

$X= \Sigma\Sigma?W_iW_{ij}X_{ij}$

where X is the final evaluated value of the geological environment quality for one type of land-use; W_i is the weighted value of criterion hierarchy's index; W_{ij} is weighted value of the index hierarchy compared to the criterion hierarchy; X_{ij} is the value of the index hierarchy's index; i and j are the number of the factor.

By using this equation the most suitable land use for any given location can be determined.

Table 4. The Criterion of geological environment of commerce and domestic land utilization

Factors	Index	Criterion standard			Weighting value (W)
Terrain degree of an incline	Reality/degree	>8	3~8	<3	0.028
	Evaluation value	20	40	80	
Active fault and the ground fissure	Reality	Existence	Potential	Not existence	0.274
	Evaluation value	10	30	80	
Buried depth of supporting course	Reality/m	>10	5~10	<5	0.077
	Evaluation value	20	60	80	
Bearing capacity of supporting course	Reality/kPa	<100	100~180	>180	0.177
	Evaluation value	10	60	80	
Buried depth of groundwater	Reality	<5	5~15	>15	0.039
	Evaluation value	20	40	80	
Surface subsidence amount	Reality/mm	>100	50~100	<50	0.055
	Evaluation value	20	60	100	
Flood water calamity	Reality	Once 10 years	Once 50 years	Once 100 years	0.167
	Evaluation value	20	60	80	
Communication term	Reality	Bad	General	Well	0.044
	Evaluation value	10	50	80	
Fundamental facilities state	Reality	Bad	General	Well	0.059
	Evaluation value	10	50	80	
Flourishing degree of business affairs	Reality	Bad	Moderate	Good	0.046
	Evaluation value	20	40	80	
Environment	Reality	Bad	Moderate	Good	0.034
	Evaluation value	10	60	100	

SWOT method applied in the land use evaluation

SWOT analysis is a simple, cost-effective tool for gaining insight into the workings of an organization. SWOT stands for strengths, weaknesses, opportunities, and threats. We can use SWOT analysis method for land use planning based upon the geological environment. When considering the sustainability and limits of the geological resources, the SWOT analysis is employed to identify the strengths (S) and/or weaknesses (W) of geological hazards compared with other geological conditions along with external factors which are likely to provide opportunities (O) for and/or threats (T) to technological change in land-use. In Nanjing city, the main geological strength is the existence of solid rock upon which foundation of buildings can be lain, the weaknesses are the geological hazards. The quality of a land-use designation can be determined by multiple sitting factors with weights of SWOT analysis.

$X_i=\Sigma W_i$

where: w_j is the SWOT factor.

Table 5 shows the factors in evaluating the storage siting.

Table 5. Multiple sitting factors with weights of SWOT analysis for storage siting

Factors	Criterion standard				
Terrain degree of an incline	Reality/degree	>8	3~8	<3	simple
	SWOT value	1	2	3	4
Distance from active fault	Reality/m	≤300	300–500	500–1000	>1000
	SWOT value	1	2	3	4
Bank stability	Reality	Strong instability	Weak instability	instability	Stability
	SWOT value	1	2	3	4
Ground water	Reality×104/a	>15m3/km2	10-15m3/km2	5-10m3/km2	≤5m3/km2
	SWOT value	1	2	3	4
Buried depth of top sand soil	Reality/m	>15	10~15	5~10	<5
	SWOT value	1	2	3	4
Type of soil	Reality	Soft soil	General soil	Sand soil	Rock mass
	SWOT value	1	2	3	4
Distance from water conserve engineering	Reality/m	On eco-protection area	≤500	500–1000	>1000
	SWOT value	1	2	3	4

Calculation of evaluation value for determining the strength of a geological hazard using the evaluation index along with criterion for different land uses, a value for the strength of geological hazards can be calculated using the AHP method.

$X_i = \lambda_i \Sigma W_j X_j$

or

$X_i = \lambda_i \Sigma W_j$

where X_i is subsystem's evaluation value; W_j is weighted value of valuation index; X_j is evaluation value of j valuation index and λ_i is the geological hazard strength index.

Based upon a value assigned to one of the four main geological hazards the values for suitable land utilization in each unit derived from the AHP method are: Suitable unit: X>80, generally suitable unit 60<X<80 and not suitable unit, X<20. The value for each element is calculated using software called GEO-ENA using:

$\lambda_i = \Sigma W_i / 4$

where w_i is the strength index of geological hazard. The geological hazard can vary different geological settings making it necessary to assess the strength of the geological hazard in every evaluation element.

The strength index can be determined according to Table 6.

Table 6. Strength index of different geological hazard

Geological hazard	Very strong	Strong	Weak	No existence
Landslide	0.1	0.2	0.5	1.0
Ground collapse	0.1	0.2	0.5	1.0
Land subsidence	0.2	0.4	0.6	1.0
Bank collapse	0.2	0.4	0.8	1.0

RESULTS

Based upon an assessment of the geological condition and long-term planning using AHP and SWOT methods, Nanjing city, can be separated into five different zones.

1. In the eastern mountainous region of the city: X<50 for buildings, the slopes are steep, landslides and ground collapses are well distributed. This part of the city is not suitable for constructing various buildings, but it is suitable for landscape development.

2. The area of the Yangzhi River alluvial plain in west of the city: the slopes are shallow, the bearing capacity is high because the sand soil, but the river bank collapse are well distributed, X>80 for harbour construction and storage use of land, it is suitable for harbour construction and storage use.

3. The area of the South of Nanjing city: terrain is flattish, bearing capacity of foundation is high, communication is convenient, it is the most ideal region for development of housing and industry construction of Nanjing city in future.

4. Along the distributed area of Qinghuai River ancient river channel: the principal geological hazard is the shallow ground water table, so, in construction process, especially in deep foundation excavation, the problem is the stability of slopes. This area is suitable for lower building construction but not suitable for tower buildings.

5. Between the Yangzhi River and Qinghuai River area: the thickness of soft soil is more than 60m. In this area, it is suitable for housing land utilization, but it must be careful in selecting the foundation type.

CONCLUSIONS

The main intent of this paper is to demonstrate the application of a conceptual method for analysis of geological conditions, hazard and land-use to support the planning process for Nanjing city. We have used a series of steps to determine the suitability and sustainability of land-use. Each step considers the geological hazards, land-use needs, and assigns values from which recommendations of land-use can be made. From the method described in this paper, n using a systematic analysis approach, it is possible to determine the land-use for different purposes based upon an understanding of the geological conditions. Different land uses n must consider the different geological environment in their long-term urban development.

Acknowledgements: The work discussed in this paper was supported by the 10th five year "211" research planning foundation of Hohai University grant XK2.4.3 and supported by National Science Foundation of Chinese grant 50579013.

Corresponding author: Prof Faming Zhang, Geology Department of Hohai University, No.1 Xikang Road, Nanjing, Jiangsu, 210098, China. Tel: +86 25 83737880. Email: Famzhang@Tom.com or Zhangfm@hhu.edu.cn.

REFERENCES

DAI, F.C., LEE, C.F. & ZHANG, X.H. 2001. GIS-based geoenvironmental evaluation for urban land-use planning: a case study. *Engineering Geology* **61** (4), 257–271.

DUFFAUT, P. 1982. Subsurface town planning and underground engineering with reference to geology and working methods. *In: Proceedings of the Regional Symposium on Underground Works and Special Foundations, Singapore.*

LIU YUHAI, CHEN ZHIXIB, NI WANKUI & ZHAO FASUO. 1997. *Studies on urban geology of Datong,* Xi'an Mapping Publish Corporation (in Chinese).

LOKIN, P. 1990. Destruction and protection of geological environment in urban areas, discussion on Beograde example. *In Proceedings of the 6th Congress of the International Association of Engineering Geology*, *Amsterdam,* **1**, 181-187. A.A. Balkema, Rotterdam.

LUO GUOYU et al.. 2000. *Geotechnique in urban environment*. Nanjing University Press

SAATY, T.L., 2003. Decision-making with the AHP: why is the principal eigenvector necessary. *European Journal of Operational Research,* **145** (1), 85-91.

SAATY, T.L. & VARGAS, L.G. 1991. *Prediction, projection and forecasting.* Kluwer Academic Publications, Boston.

STERLY, R.L. & GODARD, J-P. 2002. Geoengineering considerations on the optimal priorities in hierarchical structures. *Journal of Mathematical Psychology,* **15**, 231–281.

STERLING, R.L. & CARMODY, J. 1992. Merging Geological and Human Use Considerations in Underground Transit Station Design. *In: Proceedings of the 5th International Conference on Underground Space and Earth Sheltered Structures, Delft University of Technology.*