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A GIS-Based Evaluation of Environmental Sensitivity for an Urban Expressway in Shenzhen, China

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ABSTRACT

Urban eco-environmental degradation is becoming inevitable due to the extensive urbanization, population growth, and socioeconomic development in China. One of the traffic arteries in Shenzhen is an urban expressway that is under construction and that runs across environmentally sensitive areas (ESAs). The environmental pollution from urban expressways is critical, due to the characteristics of expressways such as high runoff coefficients, considerable contaminant accumulation, and complex pollutant ingredients. ESAs are vulnerable to anthropogenic disturbances and hence should be given special attention. In order to evaluate the environmental sensitivity along this urban expressway and minimize the influences of the ongoing road construction and future operation on the surrounding ecosystem, the environmental sensitivity of the relevant area was evaluated based on the application of a geographic information system (GIS). A final ESA map was classified into four environmental sensitivity levels; this classification indicates that a large proportion of the expressway passes through areas of high sensitivity, representing 11.93 km or 52.3% of the total expressway, and more than 90% of the total expressway passes through ESAs. This study provides beneficial information for optimal layout schemes of initial rainfall runoff treatment facilities developed from low-impact development (LID) techniques in order to minimize the impact of polluted road runoff on the surrounding ecological environment.

1. Introduction

The urban ecological environment provides people with clean water resources and a comfortable living environment, both of which are the foundation of urban economic, social, and cultural development. However, with the development of urbanization, the urban ecological environment has become increasingly vulnerable to urban flooding, the heat island effect, and rainfall runoff pollution. In order to relieve the impact of urban expansion on the environment, environmentally sensitive areas (ESAs) are commonly investigated as a preliminary means of ecosystem management. ESAs are identified so as to provide useful information for further measures to maintain the urban ecosystem health and raise public living standards.

An urban expressway that is currently under construction runs across a series of nature reserves in Shenzhen; these reserves are considered to be restricted areas for urban construction and should therefore be appropriately protected. This study evaluates the environmental sensitivity around the urban expressway based on the application of a geographic information system (GIS) in order to identify relevant ESAs and provide beneficial information for ecosystem management. Given the contradictions between urban construction and ecosystem protection, low-impact development (LID) concepts and techniques can be helpful in addressing this difficult issue and highlighting the significance of environmental protection during the urban-expansion process.

2. Methodology

2.1. Study area

The urban expressway runs from west to east and has a total length of around 22.82 km. It runs across a series of water-source reserves that are all reservoirs for drinking water; these include the Tongluojing Reservoir, Sanzhoutian Reservoir, Kuangshan

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Reservoir, Dashanpo Reservoir, Shangxiadu Reservoir, Honghualing Reservoir, and Chiao Reservoir. It also crosses the Sanzhoutian Nature Reserve and the Maluanshan Nature Reserve, as shown in Fig. 1.

2.2. Framework of the environmental sensitivity evaluation

Two types of environmental elements were specified in this study: nature reserves and water-source reserves. The environmental sensitivity level was identified based on the buffer zones specified in the water-source and nature reserve management rules, respectively, which are classified according to spatial distance from the reserves [1,2]. In order to quantify the reserve management rules and evaluate the sensitivity level within the study area, the buffer zones were graded into four levels and given a score of 7, 5, 3, and 1, respectively; the higher the score, the greater the importance of the zone and the higher the environmental sensitivity (Table 1), as suggested by the literature [3].

2.3. Environmental sensitivity evaluation process

The environmental sensitivity evaluation was carried out using a GIS platform. GIS is a useful, cost-effective, and convenient tool for evaluating environmental sensitivity by efficiently measuring, analyzing, and visualizing spatial data collected from the real world. Spatial data were first collected and arranged according to their relevance to this study; a multiple ring buffer analysis was subsequently carried out to evaluate the environmental sensitivity of each of the ESA elements, as stated in the GIS application guide [4]. The weight of each ESA element was defined based on its significance, before evaluating the overall environmental sensitivity of the study area. The significance of the ESA elements in preserving the urban ecosystem and maintaining the health of the citizens is related to their degree of scarcity, cost of reparability, and management systems. In this case, the overall weight is 1, with the water-source reserve element having a weight of 0.6 and the nature reserve element having a weight of 0.4, as referenced in the literature [5,6]. A spatial overlay analysis was then implemented; the raster overlay calculation was conducted through a superposition analysis based on the weights of each ESA element in order to

Table 1
Classifying and grading system for environmental sensitivity evaluation.

ESA elements	Buffer zone levels	Distance to water-source reserve/nature reserve (m)	Scores
Water-source reserve	Primary protection zone	< 200	7
	Secondary protection zone	200–2000	5
	Quasi-protection zone	2000–3000	3
	Non-protection zone	> 3000	1
Nature reserve	Core zone	< 500	7
	Buffer zone	500–1000	5
	Pilot zone	1000–5000	3
	Non-protection zone	> 5000	1

obtain the integrated sensitivity values, according to the multiple factor evaluation model (Eq. (1)):

$$M = \sum_{i=1}^{n} A_i \times W_i \quad (1)$$

where M is the overall environmental sensitivity value of each unit, A_i is the buffer zone score for each ESA element (i.e., $A = 1, 3, 5, 7$), W_i is the assigned weight for each ESA element (i.e., $W = 0.6$ for water-source reserve and $W = 0.4$ for nature reserve), and n is the number of the ESA element (i.e., $n = 2$ in this case).

The calculated sensitivity values were then reclassified into four classes that corresponded to four environmental sensitivity levels based on a method of natural breaks (Table 2). The final ESA evaluation was therefore obtained in the form of a thematic map in GIS.

3. Results and discussion

3.1. Environmental sensitivity evaluation for individual ESA elements

It can be seen from the obtained thematic map (Figs. 2 and 3) that most sections of the expressway lie within the water-source reserve protection zones, and some sections are close to or even

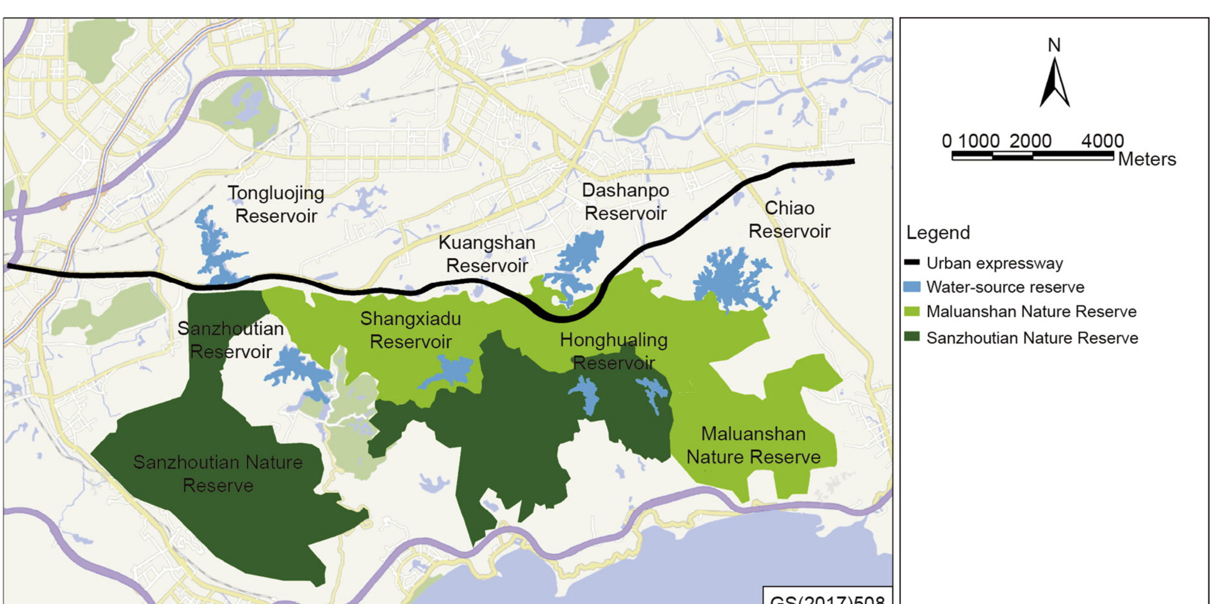

Fig. 1. The study area for the environmental sensitivity evaluation.

Table 2
Classification of the environmental sensitivity level.

ESA level	Sensitivity value	Sensitivity level
High sensitivity	$5 < M \leq 7$	1
Moderate sensitivity	$3.4 < M \leq 5$	2
Low sensitivity	$2.2 < M \leq 3.4$	3
Non-sensitivity	$1 \leq M \leq 2.2$	4

fall into the primary protection zone. In particular, a section of the expressway that is 1.49 km in length is less than 100 m away from the Tongluojing Reservoir, leading to a potential adverse impact on this drinking water source. In addition to water-source reserves, the Sanzhoutian Nature Reserve and Maluanshan Nature Reserve cover a wide range of the area; as a result, about 12.80 km, or 56.1%, of the total expressway passes through the core zone of the nature reserve. It can also be seen that a small proportion of moderately sensitive area (blue area) was identified between the high- and low-sensitivity areas. This narrow moderately sensitive area is treated as a buffer zone (500–1000 m away from the nature reserve) for protecting highly sensitive areas or core zones from human activities. Hence, areas of moderate sensitivity should also be protected.

The expressway, like other urban roads, is considered to be a primary source of rainfall runoff pollution because of contaminant accumulation on the road surface, including heavy metals such as zinc (Zn), cadmium (Cd), and lead (Pb) [7]. These pollutants will be washed off by rainfall runoff and will eventually discharge into the surrounding environment with the runoff, thereby causing water environmental deterioration and land contamination [8]. Therefore, in addition to the impact of the expressway on the utilization of water resources within the water-source reserves, its impact on the nature reserves should be considered.

3.2. Overall environmental sensitivity evaluation for the study area

It can be observed from the final thematic map (Fig. 4) that the expressway passes through the edge of highly sensitive areas close to the Tongluojing Reservoir and Kuangshan Reservoir, with more than half of the sections of the expressway (52.3%) falling into areas of high sensitivity that are considered to be prohibited areas for construction projects, irrelevant to natural resource protection (Table 3). Sufficient attention should be given to these sections, especially those near the reservoirs. In addition to highly sensitive areas, a section of the expressway that is about 6.02 km in length, or 26.4% of the total expressway, passes through areas with a moderate sensitivity level. In contrast, only around 2.68 km, or 11.7%, of the expressway passes through areas of low sensitivity, while the rest of the expressway (2.19 km in length) passes through areas with no sensitivity. Taking into consideration the adverse impact of road runoff pollution on the surrounding environment, reasonable measures should be carried out to achieve a balance between urban growth and ecosystem protection, especially for the ESAs through which more than 90% of the expressway passes.

In this case, LID techniques are considered to be a feasible way to minimize the impact of road runoff on these ESAs. LID techniques, such as bio-retention, grassed swale, and rainfall storage tanks, are conducive to controlling rainfall runoff at the source and cleansing runoff through the natural processes of detention, infiltration, and evaporation. Moreover, since LID techniques are normally microscale and decentralized, they can be beneficially applied to highly constrained areas and ESAs with fewer environmental impacts [9]. By using LID techniques and related facilities, polluted runoff from the expressway can be detained and treated without discharging it into the ESAs directly. The results of this evaluation provide useful information for guiding the layout of LID facilities based on sensitivity levels. In particular, for highly sensitive areas, rainfall runoff purification and utilization facilities should be implemented, along with emergency disposal devices and materials for road chemical leakage, in order to eliminate the potential risk of environmental damage. In contrast, for moderately sensitive areas, road runoff should be treated using LID facilities such as bio-retention before discharging it into the environment or reusing it. In addition, for areas with a low sensitivity level, since the environmental sensitivity is relatively acceptable, road runoff can be conveyed through grassed swale, in which runoff pollutants can be effectively filtered, before discharging it into the environment. For

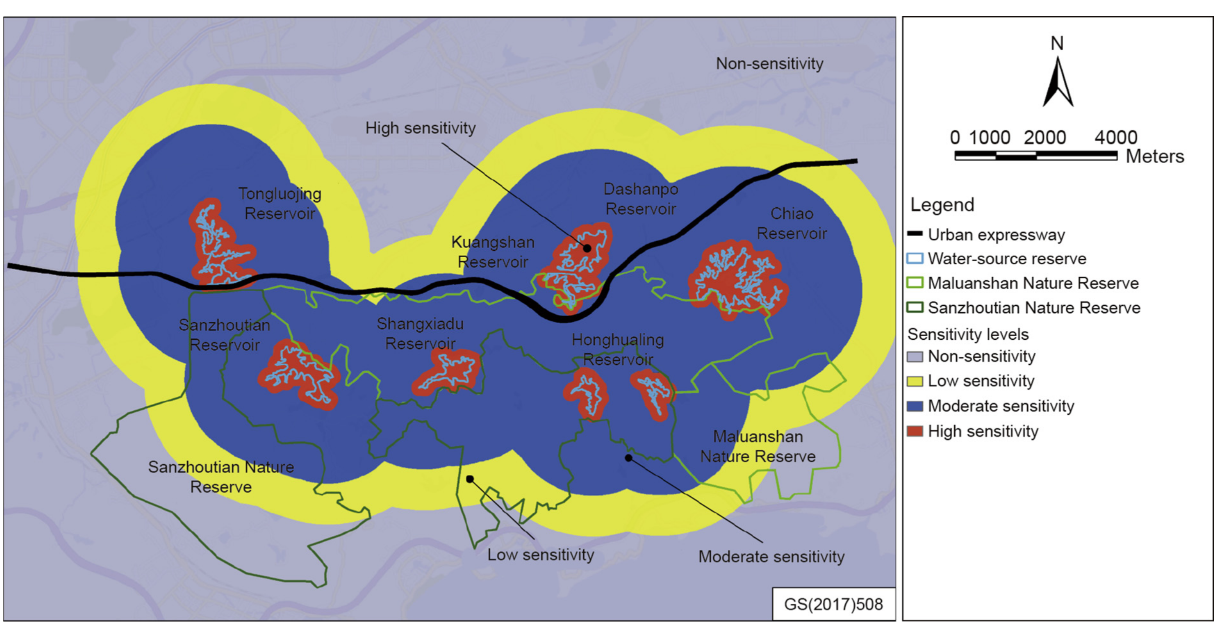

Fig. 2. Environmental sensitivity evaluation of the relevant water-source reserves based on the water-source reserve element.

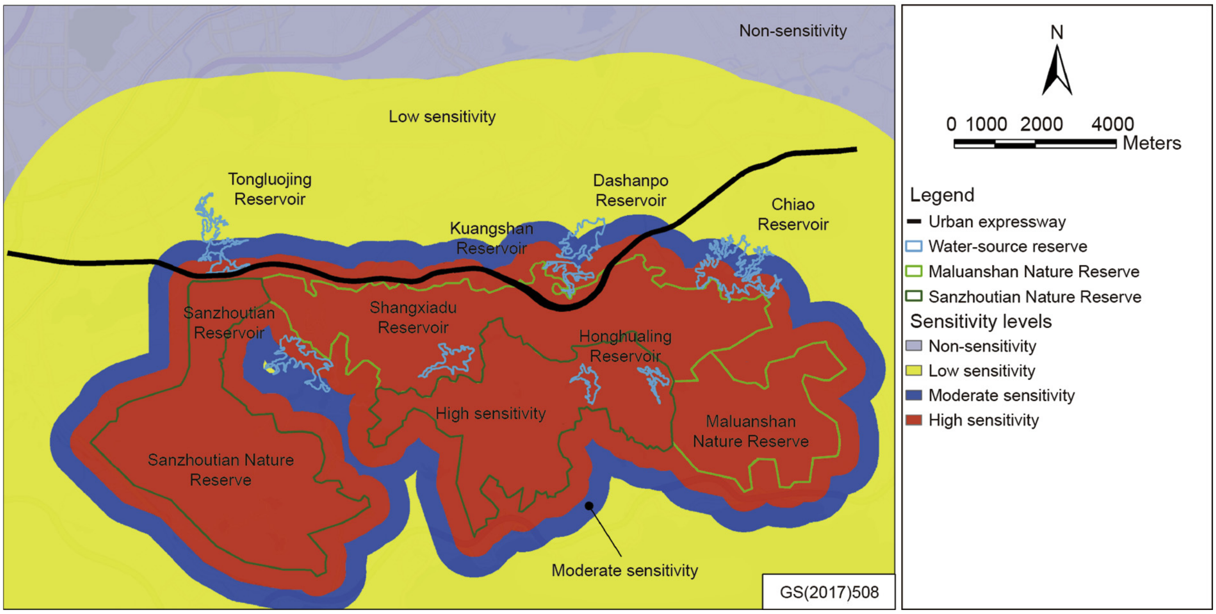

Fig. 3. Environmental sensitivity evaluation of the relevant nature reserves based on the nature reserve element.

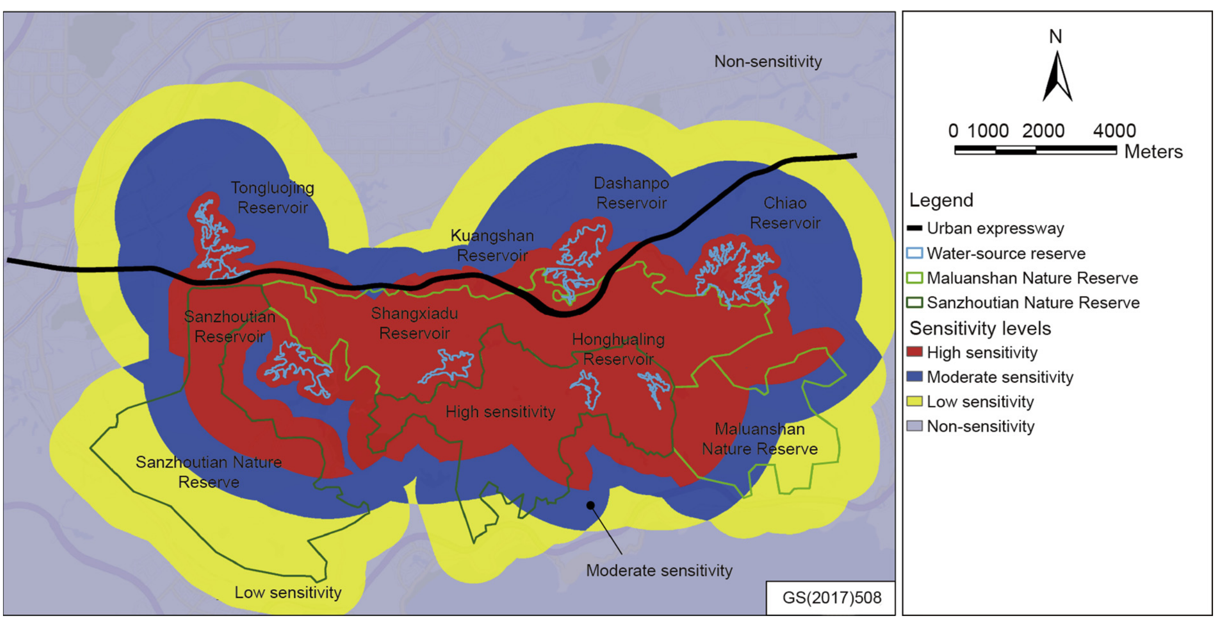

Fig. 4. Overall environmental sensitivity evaluation for the study area.

Table 3
Proportions of the expressway passing through areas of different sensitivity levels.

ESA level	Expressway length (km)	Percentage of total length (%)
High sensitivity	11.93	52.3
Moderate sensitivity	6.02	26.4
Low sensitivity	2.68	11.7
Non-sensitivity	2.19	9.6
Total	22.82	100

areas of no sensitivity, there is no need to control the road runoff; however, rainfall resource utilization based on LID techniques is still preferable in order to conserve water resources and promote sustainable development.

4. Conclusions

Most of the area through which the urban expressway passes is considered to be environmentally sensitive, and more than half of the total expressway passes through areas of high sensitivity. Based on the application of GIS, our environmental sensitivity evaluation offers direction on how potential damage to the ecological environment may be effectively reduced during this urban-expansion process. An area being classified as "sensitive" does not mean that no form of human activity is allowed within it; rather, such a classification permits a growing awareness of the importance of ecological protection and enables proper measures to be taken during urban construction.

To reduce the impact of road rainfall runoff pollution on the surrounding environment, initial rainfall runoff treatment and usage facilities developed from LID concepts are suggested as a way of addressing this tough issue. Further study will involve more indicators and will include LID implementation strategies in order to evaluate the environmental sensitivity in detail and optimize measures for maintaining the urban ecological environment. The evaluation system presented in this study and a further comprehensive system based on the proposed evaluation system, involving more extensive evaluation elements such as topography and hydrology, can also be applied in other aspects, such as natural hazard assessment and land-use planning.

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Compliance with ethics guidelines

Qian Li, Fengqing Guo, and Yuntao Guan declare that they have no conflict of interest or financial conflicts to disclose.

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