Urban Pluvial Flood Risk Assessment under Land Use Change Scenarios: A Case Study of the Maozhou River Basin, Shenzhen (Postprint)

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Abstract

Frequent rainstorm floods in recent years have become a primary disaster type threatening sustainable urban development, while land use changes alter regional landscape structures and hydrological processes, representing an important factor exacerbating urban rainstorm flood disaster risks. Quantitatively investigating the impacts of land use changes on rainstorm floods and their risks holds significant importance. Taking the Maozhou River Basin in Shenzhen as a case study, this research quantitatively simulated urban rainstorm flood disaster risks under 12 hazard-land use exposure scenarios based on the CLUE-S model, SCS model, and equal-volume inundation algorithm. The results demonstrate that under identical land use spatial patterns, urban rainstorm flood disaster risks intensify significantly with increasing rainstorm hazard. Under equivalent hazard levels, with increasing construction land area, both medium-risk and high-risk zones exhibit a relatively pronounced increasing trend, and the increase rates of medium- and high-risk zones show high synergistic variation characteristics with the increase rate of construction land area. Taking the 50-year return period hazard level as an example, as construction land area increases from 15368.85 hm^2 in the baseline period to 16076.07 hm^2 in the recent period and 16750.89 hm^2 in the future period, high-risk zone area increases from 254.07 hm^2 to 276.48 hm^2 and 286.2 hm^2. This indicates that although increased rainstorm intensity is the fundamental driver of intensified urban rainstorm flood disaster risks, the influence of land use changes—characterized by increased construction land area—on rainstorm flood disaster risks cannot be ignored.

Full Text

Preamble

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Storm Flood Disaster Risk Assessment in Urban Areas Based on Land Use Change Scenarios: A Case Study of Maozhou Watershed in Shenzhen City

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Abstract: China is one of the few countries in the world with frequent natural disasters and severe losses, characterized by multiple disaster types, high frequency, and significant damage. Flood and drought disasters are currently the most prominent types. With accelerating urbanization, coastal cities in particular have experienced dramatic changes in land use spatial patterns, marked by rapid increases in construction land. As population and wealth continuously concentrate in urban areas, urban natural disaster vulnerability gradually intensifies, and storm flood disaster risk significantly escalates. Recent frequent storm floods have attracted widespread public and media attention, causing severe losses to urban development. For instance, the July 21, 2012 Beijing extreme rainstorm caused economic losses of 11.64 billion yuan, while Shenzhen, China' s youngest city, suffered from the strongest rainstorm since 2000 in 2014, with direct economic losses of approximately 1.602 billion yuan.

Land use changes in rapidly urbanizing areas alter original landscape structures and hydrological processes, and their impacts on urban storm flood disasters have gradually attracted academic attention. Research on land use change and its eco-environmental effects has advanced significantly, particularly regarding impacts on hydrological processes. Urbanization is generally believed to increase impervious surfaces, reduce infiltration and evaporation, shorten runoff concentration time, and consequently increase surface runoff and peak flow. Increased construction land reduces surface roughness, while drainage system construction accelerates watershed convergence. Agricultural development activities increase cultivated land area and land use intensity, reducing soil infiltration rates and increasing soil bulk density, thereby increasing watershed runoff and peak flow. Although the impact of land use change on storm flood disasters largely depends on storm events and spatial scales, land cover change has been considered an important cause of frequent floods since the 21st century.

From a disaster system perspective, urban spatial growth directly changes flood-

prone environments such as impervious surfaces and river landscapes. The more unstable the disaster-forming environment, the greater the risk of urban storm flood disasters. Land use structure and landscape pattern changes characterized by increased construction land and decreased ecological land are primary reasons for increasingly severe urban flood disasters. Economic growth and unreasonable land use patterns and intensity from urbanization increase vulnerability to flood disasters. Areas with higher urbanization levels face greater flood disaster risks due to increased vulnerability and exposure.

Scenario simulation is an important research method for predicting and preventing natural disaster risks. However, most current scenario simulation studies focus on natural disaster frequency and intensity scenarios, lacking more practically meaningful socio-economic development scenario settings and risk simulations. Urban storm flood disaster risk assessment has long been a research hotspot in natural disaster studies. Focusing on land use change scenarios as spatial manifestations of socio-economic development scenarios and emphasizing the core link of land use coupling with heavy rainfall processes is an important pathway to understanding urban storm flood disaster formation mechanisms and holds significant importance for quantitative assessment of flood disaster risks under land use change scenarios. This paper simulates urban flood disaster risks under different storm scenarios based on land use change, representing a positive attempt at urban natural disaster risk assessment from a landscape ecology perspective. It helps clarify the impact mechanisms of land use change on urban storm flood disaster risks and provides landscape optimization pathways for urban storm flood disaster risk prevention, thereby enhancing urban disaster prevention and reduction capabilities, promoting new urbanization, and facilitating regional sustainable development to serve urban storm flood disaster risk management.

Keywords: land use change scenarios; storm flood disaster risk; equal volume submerged algorithm; Maozhou Watershed in Shenzhen City

1. Study Area Overview

Shenzhen City is located in the central coastal area of Guangdong Province, on the eastern shore of the Pearl River Estuary, representing a typical rapidly urbanizing region in China. The Maozhou River is the largest river within Shenzhen’ s territory in terms of watershed area, situated in the northwestern corner of the city with an asymmetric dendritic distribution. Originating from the northern foothills of Yangtai Mountain within Shenzhen, it flows from southeast to northwest and empties into the Lingdingyang Bay at Minzhu Village, Shajing Subdistrict. The Maozhou River Basin primarily includes Guangming New District’ s Gongming Subdistrict, Bao’ an District’ s Songgang Subdistrict, and parts of Shajing and Shiyan Subdistricts, covering an area of 310.85 km^2. The basin contains several reservoirs including Shiyan, Etou, Luotian, and Ejing

Reservoirs.

The terrain is high in the east and southeast, low in the west and southwest. The upstream area consists of low mountains and hills, the middle reaches are dominated by basins and plains, and the downstream area is a flat coastal alluvial plain. The basin comprises three secondary sub-watersheds: the Shiyan Reservoir sub-watershed in the upper reaches, the Yanchuan Village sub-watershed in the middle reaches, and the Gonghe Village sub-watershed in the lower reaches. The Maozhou River Basin is a typical area of urban waterlogging in Shenzhen, with a total population of approximately 1.5 million. It belongs to the south subtropical maritime monsoon climate zone, with an average annual precipitation of 1,642–1,649 mm and extremely uneven spatiotemporal distribution. Land use types are dominated by construction land and forest land, with construction land accounting for about 50% of the watershed area and forest land about 30%. Most areas of the watershed are located below 100 m elevation.

[Figure 1: see original paper] Geographical location of the study area

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2. Data Sources

The basic data used in this study mainly include: Landsat series remote sensing images (orbital paths 122/44 and 121/44) acquired on November 17, 1995; December 30, 1995; December 23, 1999; January 2, 2000; March 5, 2005; November 23, 2005; December 23, 2010; November 30, 2010; October 18, 2013; and February 6, 2014. Daily precipitation data from meteorological stations in the Pearl River Delta region were obtained from the China Meteorological Data Sharing Service Network. The 30m resolution FROM-GLC (Finer Resolution Observation and Monitoring of Global Land Cover) global land cover product was provided by the Center for Earth System Science Research at Tsinghua University. Additional data include Shenzhen road traffic distribution, soil type distribution maps from the 2013 Shenzhen Natural Resources Survey, Shenzhen administrative divisions, geological hazard distribution data from the Shenzhen Geological Hazard Prevention Public Service Network, and statistical yearbook materials. All data were uniformly projected using the Shenzhen local coordinate system.

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3. Research Methods

This study adopts the UN/ISDR (United Nations International Strategy for Disaster Reduction) definition of risk, characterizing risk as a function of hazard factors and vulnerability. It proposes an urban storm flood disaster risk assessment framework based on land use change scenarios. The flood inundation depth under different rainfall intensity hazard levels is achieved through rainfall-runoff process simulation. The sensitivity of disaster-bearing bodies under hazard sources is quantitatively assessed using vulnerability functions, which characterize the expected loss of land use types in inundated areas. The framework integrates the CLUE-S model for land use change simulation, statistical analysis of exceedance probability levels based on historical precipitation data, SCS model for runoff generation, and an equal-volume submersion algorithm combined with topographic data to determine inundation range and possible maximum inundation depth, considering rainwater storage and drainage capacity. Based on this, risk quantitative simulation and mapping are implemented to clarify landscape optimization pathways for addressing urban storm flood disaster risk.

[Figure 2: see original paper] Research framework and methodology

3.1 Urban Land Use Change Scenario Setting

Considering land use change as a process coupling natural and human systems, urban land use change scenario simulation was conducted for the entire Shenzhen area, from which the Maozhou River Basin was extracted as the risk assessment study area. The study first classified remote sensing images into eight land use types (cultivated land, orchard, forest land, construction land, water body, wetland, unused land, and grassland) based on the study area's actual conditions and spectral characteristics. After radiometric calibration, atmospheric correction, and geometric precision correction of Landsat series data in ENVI software, supervised classification was employed. The classification results were refined using improved normalized difference water index (MNDWI), normalized difference vegetation index (NDVI), and normalized difference building index (NDBI). High-resolution Google Earth images were used to select verification points in areas with no significant land use change since 1995 for accuracy assessment of the classification results.

The CLUE-S (Conversion of Land Use and its Effects at Small Region Extent) model was used for land use change scenario simulation, which has clear advantages at the regional scale. Its core components include predicting land use type demand, clarifying land use change driving mechanisms, and determining conversion sequences and relative elasticity coefficients. For land use type demand prediction, Shenzhen' s land use change characteristics over the past 20 years show continuous construction land increase and ecological land decrease. However, considering that construction land growth is constrained by policy and resources, its growth rate gradually decreases in the middle and late stages of urbanization, showing S-shaped growth similar to population development. Logistic curve models were used to predict annual land use demand from 2013, with simulated 2010 land use areas compared against interpreted results to improve reliability.

For driving mechanisms, binary Logistic regression was applied to each land use type using ten driving factors: elevation, slope, distance to roads, distance to rivers, distance to coastline, and distance to hazard points, derived from 2010 Shenzhen land use maps. Random sampling generated 3,000 sample points for stepwise regression analysis with variable entry/removal probability levels of 0.05 and 0.10. ROC (Receiver Operating Characteristic) curves were used to test regression results. Conversion sequences and relative elasticity coefficients were determined based on CLUE-S application cases and study area characteristics. The Dyna-CLUE software was used to simulate land use spatial patterns for 2016 and 2020.

3.2 Urban Storm Hazard Scenario Setting

As the primary hazard factor for urban storm flood disasters, storm events are the fundamental source of urban waterlogging. Therefore, clarifying storm intensity and frequency is crucial for risk assessment. This requires analyzing storm event intensity and occurrence probability from a risk induction perspective. Considering that both sudden heavy rainfall and regional continuous heavy rainfall can trigger urban storm floods, continuous three-day cumulative precipitation was selected as the basis for hazard scenario setting to comprehensively reflect both types.

Due to data availability limitations, 15 meteorological stations within 150 km of Shenzhen National Basic Meteorological Station in the Pearl River Delta region were selected as samples for estimating probability density and exceedance probability curves. Using non-parametric kernel density estimation in MATLAB, probability density and exceedance probability curves were plotted for each station to determine 10-year, 20-year, 50-year, and 100-year return periods as storm hazard scenarios. Ordinary Kriging interpolation, suitable for Shenzhen' s high precipitation characteristics, was used to simulate spatial distribution of three-day cumulative precipitation under the four hazard levels.

3.3 Urban Storm Flood Scenario Simulation

Storm flood disasters are common in urban areas, typically affecting urban ecosystems, production, living, and ecological environments through disaster chains. Scenario analysis is fundamental for risk assessment, helping clarify risk processes, reduce regional disaster risk, and ensure sustainable urban development. Based on storm event frequency and intensity, rainfall-runoff processes must be fully simulated to determine inundation range and depth.

The SCS (Soil Conservation Service) model, developed by the USDA in the 1950s, was used for runoff simulation. Its theoretical basis is the quantitative relationship between surface runoff and precipitation: $Q = \frac{(P-I_a)^2}{P-I_a+S}$, where Q is surface runoff, P is total precipitation, I_a is initial abstraction, and S is potential maximum retention. The dimensionless curve number parameter CN (ranging 0-100) is introduced, where $S = \frac{25400}{CN} - 254$. The CN value comprehensively reflects interception, infiltration, and other surface processes, depending on soil hydrological type, land use, slope, and antecedent moisture conditions.

Based on the 2013 Shenzhen soil type map and USDA soil hydrological group definitions, soil hydrological type spatial distribution was obtained. Using eight land use types and referring to CN value correction cases in the Pearl River Delta and Shenzhen, CN_2 values under medium antecedent moisture conditions (AMC II) were determined (Table 1). A slope factor was introduced to correct CN values: $CN_{2s} = \frac{CN_2}{3.282+0.00673\times(100-CN_2)\times\exp(-86\times slope)}$.

Runoff depth spatial distribution was calculated for base, short-term, and long-term scenarios under different storm hazard levels. The complex runoff convergence process was simulated using an equal-volume submersion algorithm, which simulates flood inundation range based on the principle that total runoff volume equals water volume within the inundated area. This method is practical, convenient, and suitable for small-scale regional flood scenario simulation. Under Python and ArcGIS, iterative algorithms were used to approximate total surface runoff volume to obtain the water level elevation of inundated areas, considering storm pipeline collection, storage, and drainage capacity.

The CN_2 value of AMC II in Maozhou Watershed

3.4 Urban Storm Flood Disaster Vulnerability Analysis

Vulnerability is a comprehensive characterization of sensitivity, resilience, and exposure of disaster-bearing bodies to storm floods, forming the basis of risk assessment. Based on eight land use types, vulnerability functions were constructed to quantify the loss-rate relationship with inundation depth. Different land use types exhibit varying water resistance characteristics, resulting in distinct loss-rate changes under the same inundation depth. As inundation depth increases, loss rates increase accordingly.

Referencing detailed vulnerability assessment studies for Costa Rica and other relevant research, vulnerability functions for different land use types under varying inundation depths were constructed. Construction land showed significantly higher vulnerability, increasing substantially with inundation depth. Grassland and unused land showed relatively lower vulnerability. Since the equal-volume algorithm simulates maximum possible inundation depth, the water depth stress in vulnerability functions represents cumulative inundation depth at pixel scale, indicating cumulative flood peak flow depth rather than static depth in actual inundation.

Vulnerability of different land use types to storm flood disaster

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4. Results

4.1 Land Use Change Scenarios

Based on interpreted land use maps for 1995, 2000, 2005, and 2010, the CLUE-S model simulated land use spatial distribution scenarios for 2016 and 2020.

For validation, the 2010 simulation was compared against interpreted results, achieving overall accuracy of 78.6% and Kappa coefficient of 0.679, meeting research requirements.

Analysis of land use changes from 1995-2020 reveals significant changes in both quantity and structure. Construction land area continuously increased, urbanization rate improved, and large amounts of non-construction land converted to construction land. From 2011-2020, constrained by natural conditions and land use spatial control policies, change rates slowed. Construction land increased slowly, mostly through spatial expansion around existing areas. Cultivated land and forest land decreased, while water bodies and wetlands remained almost unchanged. Orchard and unused land decreased rapidly, with unused land mainly being leveled but unbuilt bare soil. Grassland area showed a slight increasing trend due to urban public green space and corridor construction.

By 2016, construction land area increased by nearly 5% compared to 2013, and by 2020, it increased by about 10%. These two scenarios serve as short-term and long-term land use scenarios for risk assessment.

[Figure 3: see original paper] Modeling results of land use change in Maozhou Watershed (2011-2020)

4.2 Storm Hazard Scenarios

Based on probability density and exceedance probability curves from meteorological stations, 10-year, 20-year, 50-year, and 100-year return periods were determined as storm hazard scenarios. Ordinary Kriging interpolation produced spatial distribution scenarios of three-day cumulative precipitation.

Under the 10-year hazard level, spatial distribution was relatively uniform (standard deviation: 48.56 mm), slightly higher in the west. The 20-year scenario showed a decreasing trend from south to north. The 50-year and 100-year scenarios exhibited more pronounced regional differences, with high-value areas concentrated in the southern upstream Shiyan Reservoir sub-watershed, related to micro-topography and regional land-sea relationships. The basin average was 121.54 mm for 10-year, 159.33 mm for 50-year, and 164.92 mm for 100-year return periods.

[Figure 4: see original paper] Spatial distribution of three-day accumulated precipitation under different recurrence intervals in Maozhou Watershed

4.3 Storm Flood Scenarios

Based on the 12 hazard-land use interaction scenarios (3 land use scenarios × 4 hazard scenarios), runoff depth spatial distribution was calculated at pixel scale using the SCS model. High runoff depth areas were mainly construction land and water bodies. As return periods increased from 10-year to 100-year, runoff depth showed significant increases. For equivalent hazard intensity, total watershed runoff increased noticeably with expanded impervious surfaces.

The equal-volume submersion algorithm was used to analyze maximum possible inundation range and depth for each scenario. Inundation areas were primarily located in the plains of Yanchuan sub-watershed (middle reaches) and Gonghe sub-watershed (lower reaches), and low hilly basins in the upstream Shiyan Reservoir area, generally consistent with storm pipeline distribution patterns. High inundation depth areas appeared near outlets of secondary sub-watersheds, reflecting peak flow distribution and indicating important spatial guidance for enhancing underground drainage capacity.

For validation, media reports of urban waterlogging points were collected and spatially located. Shenzhen has approximately 80 major waterlogging points, mainly concentrated in Bao’ an District, Guangming New District, and Pingshan New District. Within the Maozhou Watershed, 18 waterlogging points were identified, primarily in the downstream Gonghe plain, middle Yanchuan plain, and upstream Shiyan Reservoir basin, highly consistent with pipeline distribution. The B_{Y20} scenario (base land use with 20-year storm) was used for validation. If a reported waterlogging point fell within 600m of simulated inundation area, it was defined as “1” (accurate); otherwise “0” . Results showed 61.1% of points were accurately simulated, demonstrating the method’ s feasibility.

[Figure 5: see original paper] Spatial distribution of runoff depth in different scenarios in Maozhou Watershed
[Figure 6: see original paper] Accuracy validation of flood scenarios in Maozhou Watershed

4.4 Storm Flood Disaster Risk

Risk was assessed across the 12 scenarios and classified into low risk (<0.33), medium risk (0.33≤R<0.66), and high risk ($ $0.66). For specific land use scenarios, risk areas expanded significantly with increasing storm hazard intensity. Under 10-year scenarios, high-risk areas were mainly in the middle reaches plain. As hazard intensity increased, high-risk areas expanded to middle and lower plain regions, also appearing in the Shiyan Reservoir sub-watershed.

Under specific hazard scenarios, high-risk areas also increased with construction land expansion, manifested by increased inundation depth and conversion to more vulnerable land use types. The relationship between construction land increase rate and high-risk area increase rate showed nonlinear synergistic characteristics. For example, under the 50-year hazard level, as construction land increased from 15,368.85 hm^2 (base) to 16,076.07 hm^2 (short-term) and 16,750.89 hm^2 (long-term), high-risk areas increased from 254.07 hm^2 to 276.48 hm^2 and 286.2 hm^2, respectively.

[Figure 7: see original paper] Storm flood disaster risk in different scenarios in Maozhou Watershed
[Figure 8: see original paper] Comparisons of storm flood disaster risk in different scenarios in Maozhou Watershed

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5. Conclusion

This study examined the Maozhou River Basin, a typical urban waterlogging area in Shenzhen, constructing land use change scenarios and storm hazard scenarios to quantitatively assess urban storm flood disaster risk across 12 hazard-land use interaction scenarios using the CLUE-S model and equal-volume submersion algorithm. This represents a positive attempt at urban natural disaster risk assessment from a landscape ecology perspective, helping clarify impact mechanisms and coupling relationships between land use change and natural disaster ecological risk.

Results show that: (1) With increasing storm hazard intensity, high-risk areas expand significantly; (2) With increasing construction land area, medium and high-risk areas also expand noticeably, showing nonlinear synergistic relationships. For example, under 50-year hazard level, as construction land increased from 15,368.85 hm^2 to 16,750.89 hm^2, high-risk areas increased from 254.07 hm^2 to 286.2 hm^2. While storms remain the primary hazard factor, the influence of land use change characterized by construction land increase cannot be ignored.

Land use change increases surface runoff, inundation area, and depth, while also raising vulnerability of disaster-bearing bodies. Therefore, strictly controlling construction land scale and optimizing land use spatial patterns are important landscape approaches for enhancing urban storm flood disaster risk prevention capabilities.

Limitations: The study could not incorporate spatial differences and temporal dynamics of urban drainage capacity into watershed convergence and flood simulation. The inundation simulation only considered comprehensive storage and discharge capacity based on pipeline attributes, without dynamic process simulation. Different construction land types (residential, commercial, industrial, transportation) were not distinguished due to difficulty in obtaining detailed classification from Landsat data, though such differentiation would be valuable for community-scale studies.

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