Postprint: Impervious Surface Growth Patterns and Their Driving Factors in Large Cities of the Middle Yangtze River

Authors: Li Zhi, Li Peng, Liu Qiang

Date: 2018-06-09T00:00:00+00:00

Abstract

Based on four periods of remote sensing imagery data from 1995, 2003, 2010, and 2015, this study investigates the 20-year growth of impervious surfaces and their driving factors in middle Yangtze River cities, using Wuhan, Changsha, and Nanchang as case studies. The results indicate that impervious surface growth in the three cities is significant, approaching warning levels, with spatial patterns exhibiting a fundamental trend of breakthrough expansion. At the present stage, Wuhan' s impervious surface growth is primarily contributed by the "scattered" growth pattern of non-point sources in suburban areas. In contrast, Changsha and Nanchang mainly derive from the "linear" extension of new urban areas and their internal "areal" infill patterns. Road investment, zoning policies, urban planning controls, fixed asset investment, real estate investment, population growth, and permeable technologies constitute the main factors influencing impervious surface growth in the three cities; however, the sensitivity of each factor' s influence differs among the cities. The three cities can mitigate impervious surface ratio growth through management measures to strengthen urban-rural planning, economic policy measures to control overheated real estate investment, social policy measures to balance regional population patterns, and technological measures to promote permeable materials and technologies.

Full Text

Preamble

ACTA ECOLOGICA SINICA ChinaXiv Partner Journal Vol. 38, No. 11 Jun., 2018 DOI: 10.5846/stxb20171212297

Impervious Surface Growth Patterns and Driving Factors in Large Cities Along the Middle Reaches of the Yangtze River

Li Zhi, Li Peng, Liu Qiang

1. College of Urban Construction, Jiangxi Normal University, Nanchang 330022, China
2. Institute of Planning and Design, Jiangxi Normal University, Nanchang 330022, China
3. College of Architecture and Urban Planning, Tongji University, Shanghai 200092, China

Abstract: Based on remote sensing imagery data from 1995, 2003, 2010, and 2015, this study examines the differential growth patterns of impervious surfaces in the cities of Wuhan, Changsha, and Nanchang along the middle reaches of the Yangtze River over the past 20 years using classical linear spectral analysis VIS model, ArcGIS hotspot analysis, and least squares linear modeling. The results show that the impervious surface areas (ISAs) of the three cities increased significantly, exhibiting a regular pattern of outward expansion. The impervious surface rates in the greenbelt surrounding areas of Wuhan, Changsha, and Nanchang have reached 8.9%, 7.9%, and 7.4% respectively, which are close to the internationally recognized early warning level of 10%–20%. The ISA growth of the three cities gradually spread from the old city to surrounding areas. Wuhan has broken through the greenbelt via "sporadic" growth, while Changsha and Nanchang are transitioning from a "point + line" to a "surface" ISA growth pattern, also showing a trend of breaking through the greenbelt. Due to differences in urban development stage and historical conditions, impervious surface growth in Wuhan arises mainly from sporadic growth in suburban areas. Expansion in Changsha and Nanchang is primarily due to "axis + block filling" extension growth in newly developed areas. Road investment, zoning policy, urban planning control, fixed asset investment, real estate investment, population growth, and water penetration technology are the main factors affecting impervious surface growth in the three cities, but the sensitivity of each factor differs among the cities. For Wuhan, the priority policy for reducing the ISA rate is to control out-of-greenbelt space, which can be strengthened via a rural construction planning permission system. Secondly, applying advanced technology to the greening transformation of the old city, reducing the density of real estate construction and infrastructure investment, optimizing population density distribution, and balancing city population with city ecology can also alleviate ISA growth trends. For Changsha and Nanchang, the primary method for controlling ISA increase is to control undeveloped areas in the inner greenbelt zone. The guiding principles of "precise controlling new area," "preventive controlling the suburbs," and "enhanced controlling the old area" should be applied to avoid expanding the ISA pattern. On the other hand, it is important to improve ISA by including smart urban and rural planning, increasing the rate of green space planning, balancing the population of districts, advocating profit-priority construction of urban infrastructure, and accelerating the use of advanced permeable materials and construction technologies.

Keywords: Impervious surface; growth pattern; driving factor; cities along the

middle reaches of the Yangtze River

Funding: National Natural Science Foundation of China (41501167); Jiangxi Provincial Social Science Planning Youth Project (14YJ04)

Received: 2017-12-21; **Revised:** 2018-03-15

Corresponding author. E-mail: gmorning1985@jxnu.edu.cn

Introduction

Impervious surfaces disrupt the hydrological connection between urban land surfaces and groundwater, and are considered important elements in urban ecological processes and key indicators for measuring urban health quality. Since the beginning of the new century, research on urban impervious surfaces in China has intensified, yielding substantial results in metropolitan area health evaluation, vegetation and biodiversity change processes, and urban ecological environment irreversible early warning. These studies can be summarized into two main streams: first, tracking the latest international techniques in impervious surface research, including remote sensing monitoring technologies and related parameters; and second, using impervious surfaces as an entry point to investigate the mechanisms of local urban ecological and environmental processes across different regional scales and precision levels. Although domestic research continues to deepen, several improvements remain necessary. First, the research scope is relatively limited, with disproportionate focus on coastal developed cities, which hinders the formation of comprehensive perspectives on how impervious surfaces affect China' s urban ecological environment. Research on major cities in central and western regions is particularly scarce. Second, studies tend to focus more on technical aspects of remote sensing measurement and observational phenomena, with relatively weak exploration of influencing factors and mechanisms, making it difficult to propose effective control measures.

The urban agglomeration in the middle reaches of the Yangtze River represents an important ecological security region in China, and its changing ecological environment concerns the stability of China' s ecological security pattern. Wuhan, Changsha, and Nanchang are important provincial capital cities in this region, as well as large cities with high primacy in central China' s less developed areas. In recent years, these three cities have experienced rapid expansion in population, scale, and urban form, leading to various regional urban ecological environmental problems, including different degrees of urban heat island effects. This has made urban permeability performance a focus of attention across sectors. Based on analysis of impervious surface growth patterns and evolution, this study explores the growth patterns of impervious surface distribution in large cities along the middle reaches of the Yangtze River, providing references for management priorities and measures to control urban impervious surfaces, and serving as a catalyst for fellow scholars to conduct impervious surface research in less developed central and western regions of China.

1 Data Sources

1.1 Remote Sensing Data

Landsat 8 remote sensing imagery from the US Landsat satellite program was used, with all data selected from winter months to minimize seasonal variation. Landsat 5 TM data from 1995 and 2003, and Landsat 7 ETM+ data from 2015 were processed using ENVI 5.2 software for geometric correction, atmospheric correction, and conversion to multispectral reflectance. All imagery was unified to 30 m resolution.

1.2 Socioeconomic Data

Other economic and social data were obtained from annual urban statistical yearbooks and national statistical yearbooks for the corresponding years. For comparative purposes, the study area was defined by extending approximately 51.9 km × 51.9 km (2,700 km^2) outward from the old city center of each city, encompassing the outer boundary designated by each city' s urban planning green space ecosystem. This area can be regarded as the expansion boundary that should not be breached in recent construction, as well as a protective zone for the hydro-atmospheric-biological environment of the urban population core area, possessing certain watershed significance.

2 Methodology

2.1 Linear Spectral Unmixing Technique

The Vegetation-Impervious-Soil (V-I-S) model was employed to decompose non-water ground components in the three cities using ENVI 5.2 software. The methodology purified the endmember characteristics of each component across different periods for each city, and comprehensively determined the characteristic spectra of high-albedo endmembers, low-albedo endmembers, vegetation endmembers, and soil endmembers. Constrained linear spectral unmixing was used to extract the fractional abundance of each endmember per pixel while ensuring the sum of all endmember fractions equaled 1. Given that both high-albedo and low-albedo endmember characteristic spectra exhibit certain features of impervious surfaces, the sum of the two endmember fractions was set as the impervious surface ratio. A longitudinal year normalization method based on typical sample plots was applied to eliminate temporal comparison effects. Specific technical details are available in reference [16].

2.2 Hotspot Analysis and Its Improvement

The Getis-Ord G*i index analyzes information within sub-regions to identify spatial heterogeneity and distinguish hotspot and coldspot distributions, reflecting* *the degree of association between a region and its neighboring units. To facilitate interpretation, G*i was standardized by its standard deviation. Positive G*i values indicate spatial clustering of hotspots where values around location i are significantly higher than the mean, while negative values indicate coldspots.

The spatial weight matrix Wij is a crucial component in this calculation. Traditional Wij settings often use square spatial units, which introduces errors in spatial distance weighting. To avoid this imprecision, this study employed regular hexagons as the basic spatial analysis unit to reduce potential unscientific results from unreasonable spatial proximity weight settings. To reduce computational load, standard units of 100 hm^2 area were used to measure G*i across the study area.

2.3 Growth Pattern Classification and Measurement

For analytical purposes, impervious surface growth patterns were classified based on different growth sources and spatial orientations. The patterns include: infilling growth model, road traction growth model, satellite filling growth model, and sporadic enclave growth model. By overlaying and analyzing interpreted raster data, the proportion and total area of impervious surfaces within each pattern' s scope can be obtained. Combined with multi-temporal data, the scale and speed of various growth patterns at different stages can also be measured. The basic connotations and characteristics of each pattern are detailed in Table 1.

Four types of impervious surface growth patterns and their definitions and characteristics

Model	Scope	Source of Growth	Characteristics
Infilling Growth Model	Within built-up area	Renovation of old houses and municipal facilities	Intensive development
Road Traction Growth Model	500m buffer of main roads outside old city	New construction, expansion, and renovation of road projects	Linear extension along roads
Satellite Filling Growth Model	Within greenbelt area excluding road buffers	Factory and housing construction excluding road projects	Filling development in new areas

Model	Scope	Source of Growth	Characteristics
Sporadic Growth Model	Outside greenbelt area	Scattered development outside planned areas	Leapfrog expansion

3 Results and Analysis

3.1 Impervious Surface Growth Characteristics

Analysis results show significant growth in impervious surface area across all three cities, with distribution gradually expanding from old city areas to surrounding regions. The completely impervious surface areas of Wuhan, Changsha, and Nanchang in 1995 were 4891 hm^2, 5415 hm^2, and 7207 hm^2 respectively, accounting for 1.8%, 2.0%, and 2.7% of the study area. By 2015, these values increased to 2538 hm^2, 2222 hm^2, and 1390 hm^2 respectively, representing increases of 254 hm^2, 139 hm^2, and 221 hm^2. Changsha showed the largest growth amplitude. From a temporal perspective, the 2010–2015 period exhibited growth rates nearly equivalent to the previous two decades combined, indicating an accelerating trend.

[Figure 1: see original paper] Interpretation of impervious surface rates in Wuhan, Changsha, and Nanchang in 1995, 2003, 2010, and 2015

3.2 Evolution of Impervious Surface Growth Hotspots

According to hotspot analysis results, the global G*i statistics for impervious surface growth in all three cities exceed their respective annual mean expectations, with significant statistical test values, indicating obvious clustering of growth hotspots. Over the past 20 years, Wuhan' s impervious surface growth hotspots have been distributed outside the greenbelt area, while Changsha and Nanchang' s hotspots remain within the greenbelt. This demonstrates that Wuhan' s growth pattern is gradually shifting from concentrated to dispersed, with contributions primarily from suburban areas. In contrast, Changsha and Nanchang maintain relatively concentrated growth patterns focused on newly developed areas within the greenbelt outside the old city.

[Figure 2: see original paper] Comparison and differentiation of hotspots in impervious surface extension across the three cities

3.3 Dominant Growth Patterns and Their Changes

Growth pattern analysis reveals that the contribution order of various patterns for Nanchang and Changsha is road traction > satellite > infilling > sporadic, while for Wuhan it is satellite > road traction > infilling > sporadic. Detailed results are shown in Table 2.

Comparison of dominant impervious surface growth patterns across the three cities

Growth Model	Wuhan	Changsha	Nanchang
Infilling	Initial ISA/hm^2: 34+120	88+222	34+365
Road Traction	2003: 38+45	2003: 36+256	2003: 22+312
Satellite	2005: 23+112	2005: 64+211	2005: 99+277
Sporadic	2015: 52+96	2015: 69+156	2015: 36+226

The evolution of dominant patterns shows that road traction has been Nanchang' s leading mode, though its contribution is declining. Satellite growth ranks second, while sporadic growth shows an increasing trend. Changsha follows a similar pattern, with road traction contributing most but decreasing over time, satellite growth rising, and sporadic growth increasing rapidly. Wuhan' s dominant pattern is satellite growth, which has recently given way to sporadic growth, though road traction maintains a stable and substantial contribution.

The pattern evolution reveals several key trends: (1) Road traction contributions follow an inverted U-shaped curve, rising then falling, indicating that old city areas' influence on growth is no longer dominant. (2) Infilling contributions have decreased from approximately 15% to 5%, showing that old city renovation contributes less to growth and is being replaced by satellite and sporadic patterns. (3) The stable decline in infilling and the increasing contribution of satellite and sporadic patterns suggest that road infrastructure remains important, but control priorities should focus on preventing sporadic suburban contributions and new area expansion.

4 Driving Factors Analysis

4.1 Analytical Framework

Based on the 1995, 2003, and 2015 data, a mathematical modeling framework was developed to identify driving factors. The mechanism considers: (1) Economic development level as the fundamental driver of urban construction; (2) Population growth and consumption capacity enhancement increasing demand for residential, commercial, and infrastructure land; (3) The evolution from initial concentration to outward expansion showing that road construction and location conditions are highly correlated with impervious surface growth; (4) Urban planning policy and zoning as important inductive forces; (5) Green building engineering technology as a mitigating factor.

Given that some indicators cannot be quantified and historical data are missing, the study uses linear least squares regression modeling with impervious surface ratio as the dependent variable Y (with superscripts indicating year, e.g., Y^{2003}). Independent variables include: economic development level density X_1, fixed asset investment density X_2, urban population density X_3, social retail sales density X_4, real estate investment density X_5, urban planning green space ratio X_6, road density X_7, new building green building ratio X_8, and regional zoning variable X_9. Variable definitions and calculations are detailed in Table 3.

Description and explanation of influencing factors

Variable	Notation	Definition & Calculation
Dependent	Y	Impervious surface ratio in modeling units
	Y_{in}	Ratio within greenbelt area
	Y_{out}	Ratio outside greenbelt area
Independent	X_1	Economic development level density (billion yuan/km^2, kernel density interpolation)
	X_2	Fixed asset investment density (10,000 yuan/km^2)
	X_3	Population density (10,000 persons/km^2)
	X_4	Social consumption density (10,000 yuan/km^2)
	X_5	Real estate investment density (10,000 yuan/km^2)
	X_6	Planned green space ratio (from urban planning)
	X_7	Road density (inverse distance interpolation)
	X_8	Green building ratio in new construction (from statistical yearbooks)
	X_9	Zoning factor (1=inside greenbelt, 0=outside)

4.2 Analysis Results

Using stepwise variable addition for model optimization, the entry order of variables represents their correlation strength with the dependent variable. Road density consistently enters the model first with positive coefficients, indicating it is the most significant contributor to impervious surface growth across all three cities. Roads form the urban skeleton and prerequisite for growth, while also being natural components of impervious surfaces. Urban residential, industrial, and new development areas tend to expand along roads, creating both direct and indirect contributions to impervious surfaces.

Model coefficients show that: (1) Road density' s positive coefficient is larger in Nanchang than Changsha, and larger within greenbelts than outside; (2) The coefficient decreases in newer periods, corresponding to the weakening road traction pattern over time and space; (3) Wuhan, which had already become a megacity with two million people in the 1990s and benefited from its regional hub status along the Beijing-Guangzhou corridor, shows lower road-driven intensity than Changsha, which is still establishing itself as a regional center.

Fixed asset investment and real estate investment show strong correlations with impervious surface growth. Statistical data reveal that between 2003–2010 and 2010–2015, the three cities experienced explosive growth in real estate construction, with built-up areas reaching 535 km^2, 313 km^2, and 350 km^2 respectively by 2015. Completed building areas in 2015 were 7725, 6363, and 4001 (units not specified), requiring massive fixed asset investments. As urban populations grow, demand for housing and commercial facilities increases, driving infrastructure and real estate development.

Urban planning and zoning factors demonstrate significant influence. In the 2015 overall regional model, the zoning factor X_9 shows the second-largest coefficient after road density, with values of 4.11, 1.63, and 2.38 for the three cities respectively. This positive relationship confirms that urban spatial policy fundamentally controls impervious surface patterns. The coefficient' s increasing trend over time indicates growing influence of real estate and urban investment factors.

The green building ratio variable X_8 enters models as an important factor, but unexpectedly shows positive coefficients in most city models (except Wuhan Y^{2015}). Field observations reveal that in contemporary construction practices in Changsha and Nanchang, especially in new districts, underground spaces, gardens, and green spaces are often paved with highly impervious materials like concrete and asphalt to reduce costs and improve efficiency, falling far short of true green building requirements. Limited regulatory technology and absent legal standards hinder effective supervision. Therefore, accelerating the adoption of advanced permeable engineering technologies in these developing cities is crucial for mitigating impervious surface expansion.

5 Conclusion

The impervious surface growth trends in Wuhan, Changsha, and Nanchang are significant, with growth hotspots gradually diffusing from old city areas to surrounding new districts. Wuhan has already broken through the greenbelt, while Changsha and Nanchang are in transition stages. The excessively rapid impervious surface growth exerts pressure on urban ecological environments and presents challenges to sustainable development.

Currently, the completely impervious rates within greenbelt areas have reached 8.9%, 7.9%, and 7.4% respectively, approaching the internationally recognized early warning level of 10%-20%. Spatially, the priority for Wuhan is controlling impervious surface growth in outer suburban areas. Other measures include strengthening rural construction planning permit systems, reducing real estate construction density and excessive infrastructure investment in new districts, optimizing population density distribution, and establishing balanced urban population-ecology patterns.

For Changsha and Nanchang, the spatial priority is controlling undeveloped areas within existing greenbelts. The guiding principles of "precise control of new areas," "preventive control of suburbs," and "enhanced control of old areas" should be applied to avoid pattern expansion. Additionally, improving urban and rural planning, increasing planned green space ratios, balancing district populations, prioritizing urban infrastructure construction, and accelerating the introduction of advanced permeable materials and construction techniques are essential measures.

6 Discussion

During driving factor modeling, social retail sales density X_4 showed poor linear correlation, likely because its relationship with impervious surfaces is indirect rather than direct like fixed asset or real estate investment. Its composite nature across primary, secondary, and tertiary industries creates deviation in detecting linear relationships. Some unquantifiable variables were also excluded from modeling. Future research could incorporate these factors for more precise risk prediction and management.

References

[1] Yuan F, Wu C S, Bauer M E. Comparison of spectral analysis techniques for impervious surface estimation using Landsat imagery. Photogrammetric Engineering & Remote Sensing, 2008, 74(8): 1045-1055.

[2] Conway T M. Impervious surface as an indicator of pH and specific conductance in the urbanizing coastal zone of New Jersey, USA. Journal of Environmental Management, 2007, 85(2): 308-316.

[3] Xian G. Analysis of impacts of urban land use and land cover on air quality in the Las Vegas region using remote sensing information and ground observations. International Journal of Remote Sensing, 2007, 28(24): 5427-5445.

[4] Yuan F, Sawaya K E, Loeffelholz B C, Bauer M E. Land cover classification and change analysis of the Twin Cities (Minnesota) Metropolitan Area by multitemporal Landsat remote sensing. Remote Sensing of Environment, 2005, 98(2-3): 317-328.

[5] Weng Q H, Lu D S. A sub-pixel analysis of urbanization effect on land surface temperature and its interplay with impervious surface and vegetation coverage in Indianapolis, United States. International Journal of Applied Earth Observation and Geoinformation, 2008, 10(1): 68-83.

[6] Zhang Y S, Odeh I O A, Han C F. Bi-temporal characterization of land surface temperature in relation to impervious surface area, NDVI and NDBI, using a sub-pixel image analysis. International Journal of Applied Earth Observation and Geoinformation, 2009, 11(4): 256-264.

[7] Reilly J, Maggio P, Karp S. A model to predict impervious surface for regional and municipal land use planning purposes. Environmental Impact Assessment Review, 2004, 24(3): 363-382.

[8] Xian G, Crane M, Su J S. An analysis of urban development and its environmental impact on the Tampa Bay watershed. Journal of Environmental Management, 2007, 85(4): 965-976.

[9] [Chinese reference on multi-source remote sensing for impervious surface estimation]

[10] [Chinese reference on land use change in Tarim River mainstream area]

[11] Hu X F, Weng Q H. Impervious surface area extraction from IKONOS imagery using an object-based fuzzy method. Geocarto International, 2011, 26(1): 3-20.

[12] Zhang Y J, Chen L, He C. Estimating Urban Impervious Surfaces Using LS-SVM with Multi-scale Texture. Proceedings of 2009 Joint Urban Remote Sensing Event. Shanghai, China: IEEE, 2009: 1-6.

[13] [Chinese reference on impervious surface index in Shenzhen]

[14] [Chinese reference on impervious surface and rainfall runoff]

[15] [Chinese reference on urban land use ecological effects]

[16] [Chinese reference on sample-based normalization for impervious surface monitoring]

[17] [Chinese reference on urban expansion and flood impacts]

[18] [Chinese reference on river ecosystem response to impervious surfaces]

Note: Figure translations are in progress. See original paper for figures.