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Uncovering the Spatiotemporal Dynamics of Urban Infrastructure Development: A High Spatial Resolution Material Stock and Flow Analysis

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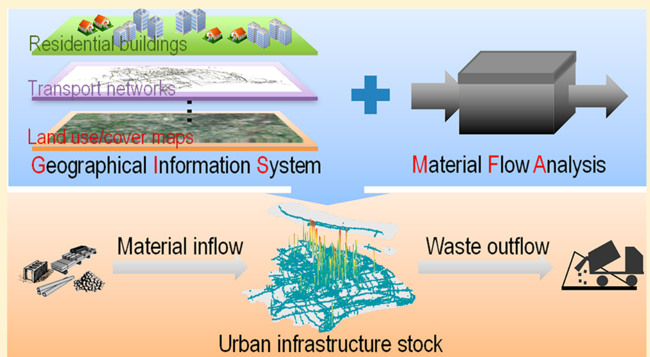
Supporting Information

ABSTRACT: Understanding the complexity and sustainability of infrastructure development is crucial for reconciling economic growth, human well-being, and environmental conservation. However, previous studies on infrastructure's material metabolism were mainly conducted on a global or national scale, due largely to lack of more spatially refined data, and thus could not reveal the spatial patterns and dynamics on a city scale. Here, we integrated material flow analysis (MFA) and geographical information system (GIS) data to uncover the spatiotemporal patterns of the material stocks and flows accompanying the infrastructure development at a high spatial resolution for the case of Shanghai, China. From 1980 to 2010, material stocks and waste output flows of Shanghai's infrastructure system exhibited a significant increase from 83 to 561 million metric tons (Mt) and from 2 to 17 Mt, respectively. Input flows peaked in 2005 because of the economic slowdown and stepped-up policies to cool the housing market. Spatially, the center and peri-urban areas were the largest container of material stocks and biggest generator of demolition waste, while suburban areas absorbed 58%−76% of material inputs. Plans to make the city more compact will enhance the service capacity of stocks but may also increase the use of more energy and emissions-intensive construction materials (e.g., steel). Prolonging the service lifetime of infrastructure through proper management and increasing the recycling and reuse rate of demolition waste are also identified as highly efficient strategies.



1. INTRODUCTION

If cities were compared to living organisms, urban infrastructure could be regarded as the flesh and bones that support the functions and activities of the urban body. The development of urban infrastructure not only plays an important role in securing economic growth and human well-being but also poses great environmental challenges to sustainability, as it is an essential part of resource and energy metabolism.[1,2] Urban infrastructure normally contains large amounts of materials and exists in societies for decades or even centuries. This entails a massive flow of materials between the natural environment and the human society during the entire lifespan of infrastructure from construction to maintenance, use, and demolition and waste management. Moreover, each life cycle stage of infrastructure is also associated with significant amount of energy use and greenhouse gas emissions.[3,4] The advancement of sustainability science[5] and the recent emergence of the science of infrastructure ecology[6] both indicate the urgent need for the exploration of the complexity and sustainability of urban infrastructure.

In order to quantify the resource and environmental impacts of infrastructure development and to design effective policies for reducing environmental impacts and improving infra-

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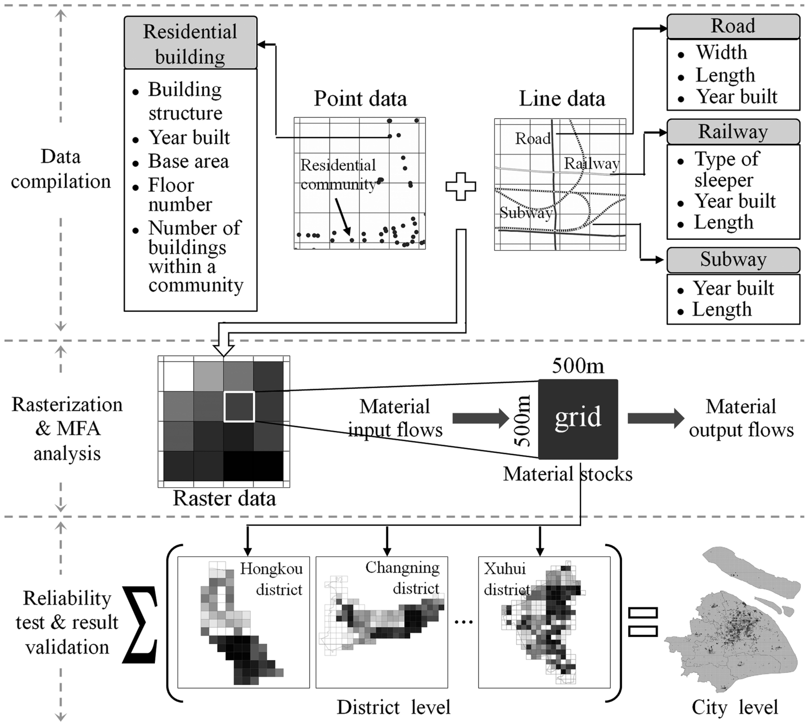

Figure 1. Workflow for the spatial material stocks and flows analysis of infrastructure development.

structure performance, a systematic investigation of infrastructure stocks and their associated material flows is needed. Material flow analysis (MFA) provides an assessment framework for understanding material throughput in human society, its historical characteristics and future trends, and implications for sustainable resource utilization.[7] Since its first development in the 1970s, this method has been used in an increasing number of literature contributions on the exploration of environmental impacts and mitigation strategies of different types of infrastructure, such as buildings,[8,9] transport networks,[10,11] motor vehicles,[2,12] power plants,[3,13] sewage systems,[14] and industrial sectors.[15,16] However, most of these studies were carried out at global[3,4,13,15] and national[2,8−12,16] scales, as national statistics on population, economy, and infrastructure's magnitude and attributes are usually readily available. The application of MFA to infrastructure at city scale, in contrast, is found to be difficult because of the lack of spatially refined data for cities.

The world is becoming more urbanized, with over 50% of the population currently residing in cities, and the share is expected to exceed 67% in 2050.[17] Cities have become the most important drivers for socio-ecological and environmental problems. For example, cities consumed 60% of global residential water and 76% of global wood for industrial purposes and accounted for over 70% of global carbon emissions.[18] Developing solutions for these far-reaching problems associated with urban resource consumption is thus crucial for addressing the grand challenges of achieving global sustainability. There are several studies that attempt to characterize infrastructure development and its environmental effects at city, district, and grid cell level. For example, Kleemann et al.[19] investigated the spatial distribution of building stocks within the municipal area of Vienna based on geographical information system (GIS) data. Van Beers and Graedel[20,21] employed proxy indicators and the GIS to analyze the magnitude and spatial distribution of in-use stocks of copper and zinc in Cape Town. Tanikawa and Hashimoto[22] used the GIS to assess the material stocks and potential waste generation of aggregated infrastructure within a small area of Manchester (U.K.) and Wakayama (Japan); Reyna and Chester[23] estimated the building turnover volume and embedded environmental impacts in Los Angeles County based on U.S. decadal building census data. Tanikawa et al. (2015)[24] analyzed the spatial and temporal characteristics of in-use material stocks of infrastructure in Japan at a 1 km grid resolution. However, systematic knowledge about the amount, structure, and material composition of infrastructure in an entire city, their impacts on resource utilization, and their changing patterns both in space and over time remains limited, especially for cities in developing countries.

In this paper, we select Shanghai as a case study to investigate urban infrastructure development and its policy implications for mitigating the environmental impacts under a rapid urbanization process. As one of the biggest cities in China, Shanghai had an area of 6340 km^2 and a population of 24 million in 2013. Since the fast urbanization began (approximately from the early 1980s),[25] it has witnessed a rapid urbanization with the share of urban population (defined as the people residing in cities and towns for more than six months) in the total increased by 1.5 times, reaching 87% in 2015, and its economic output grew at a rate of 10% per annum, reaching 403 billion U.S. dollars in 2015 (similar to that of Belgium and Iran already).[17,26] Accordingly, its urban infrastructure has also shown an unprecedented development, and several have already reached the world's greatest in terms of scale and capacity. For example, Shanghai owns the world's most extensive subway systems, with a total length of 617 km in 2015.[26] On the other hand, some other types of infrastructure may still grow significantly. For instance, the per capita floor area of residential buildings has been greatly

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expanded from 3.8 m^2 in 1980 to 24 m^2 in 2015. However, this is still much lower than the average level in European Union (EU) countries (34 m^2/capita in 2008),[27] suggesting there is still much room for improvement. Moreover, the enhancement of both the quantity and the quality of urban infrastructure has been emphasized by the national and municipal governments in their mid- and long-term socioeconomic development plans.[28] In summary, because of its large-scaled, young, yet still growing urban infrastructure, we believe Shanghai is a good case study both for the comparison with patterns of infrastructure development in mature cities in developed countries and for benchmarking future development of cities in other parts of China and other developing countries.

Specifically, we aim to answer the following questions in this paper:

(i) What is the current amount of material stocks in Shanghai's urban infrastructure after a period of fast urbanization? How large are the current and historical material flows into and the waste flows out of its infrastructure system?

(ii) What are the different changing patterns of material stocks and flows associated with different infrastructure development both in space and over time?

(iii) What are the policy implications for sustainable urban infrastructure development and urban sustainability?

2. MATERIALS AND METHODS

Figure 1 shows our workflow that combines GIS and MFA for interpreting the spatiotemporal dynamics of material stocks and flows associated with urban infrastructure development in Shanghai. We first compiled different types of data for infrastructure, rasterized data and calculated grid-level material flows and stocks, and finally performed model reliability tests at both the district and city levels and final result validation.

We included only four major types of infrastructure in this analysis, namely, residential buildings, roads, railways, and subways, because of data availability and their relatively large proportions in total infrastructure. The time horizon is from 1980 to 2010. Eight types of major construction materials, i.e., steel, cement, lime, mineral construction aggregates, glass, wood, brick, and asphalt, were taken into account in accordance with our former studies at the Chinese national level.[9,11]

2.1. Data Compilation. Officially published city-level data on the amount, construction structure, year built, material composition, and spatial distribution of infrastructure are often incomplete and not accessible to the public. Therefore, we used the emerging big data provided by some commercial companies and agencies (such as Google maps, Baidu maps, Web site of real estate agencies, and car navigation data) to address this gap. Generally, three types of infrastructure data, namely, spatial distribution, attributes, and scales, were compiled for analysis.

2.1.1. Residential Buildings. Although there are some data on the historical changes and material metabolism of some typical buildings in China,[29] it is impossible to obtain the data of all individual buildings for an entire city. As shown in Table S1 in the Supporting Information, we collected the geographical location information on residential buildings from the point of interest (POI) of residential communities as a proxy, which are provided by AutoNavi Company covering the entire city in 2005 and 2010. For the data before 2000, we used the land use and land cover maps; historical atlases; aerial photos; city layout records; and historical pictures from 1980, 1990, 1995, and 2000 for reference to rebuild the distribution of residential communities in the corresponding years. Historical hard-copy maps containing the spatial location of residential communities were digitalized, geometrically corrected, and stitched. In addition, the land use and land cover data, especially the urban land produced from Landsat MSS, TM/ETM+ images, were used to ensure all the POIs of residential communities are located within the urban boundary. The remote sensing images were first preprocessed by employing commonly used remote sensing techniques and ENVI software, which included geometric correction and image stitching. Then, by using a man−machine interactive interpretation method, the land use and cover in a 30 m × 30 m spatial resolution for the whole city were classified into six categories: cropland, forest, grassland, water, urban, and other. The classification accuracy was tested through a visual inspection method, which compares the classification result with the ground reference data such as Google earth maps, Baidu maps, and aerial photos. By creating 1000 equalized random sampling points in the classified land use and cover map and counting the number of points that were correctly classified, we calculated the overall accuracy was 85.1% for 1990, 87.2% for 2000, and 88.1% for 2013, which is good enough to meet the minimum standard of 85% proposed by the United States Geological Survey.[30]

The attributes of residential buildings, such as the numbers of buildings per community, base area (building footprint), numbers of floors, construction structure, and year built were collected from the webpage of one of the largest real-estate agencies in China (SouFun, http://soufun.com/), as it provides detailed information on residential communities and individual buildings. In addition, we further validated and supplemented the attribute information from SouFun by conducting a field survey in March 2013 and August 2014, during which a total of 73 randomly selected residential communities covering 18 districts of Shanghai were investigated. Notably, though multifunctional use does exist in the residential communities (for example, some communities contain commercial facilities such as convenience stores and restaurants), the significance of these commercial facilities is assumed to be negligible compared to that of residential buildings based on our field survey. Nonresidential buildings (including industrial, commercial, and public buildings) are not included in the analysis because of the data availability, though their floor space was about 80% of that of residential buildings in 2010.[26]

2.1.2. Transport Network (Roads, Railways, and Subways). Similar to residential buildings, spatial distribution data of the transport network in 2005 and 2010 were obtained from the company AutoNavi. Data before 2000 were digitalized from transport atlases, remote sensing images, and Google and Baidu maps. Here, to ensure the data consistency, we digitalized only the roads with a surface width above 30 m because the minimum spatial resolution of remote sensing images was 30 m. This means the roads considered in this study included only three classes (highway, first-class, and second-class, which cover about 40% of the length of all five classes) of all road systems according to the "Provisional Regulations for Urban Planning Quota Index" issued by the Ministry of Housing and Urban-Rural Development of China.[31] After the preparation of vector data sets of the

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three types of transport networks, we transferred them into raster data by setting the grid size as 500 m × 500 m so that it was consistent with the data layer of residential buildings.

Attributes of transport networks such as year of construction, road width, and tie type of rails were compiled from the Web site of Shanghai Metro, Shanghai Road Administration Bureau, and design codes. Because the information on the year of construction of road systems was available only for those major road classes (e.g., inner-ring, middle-ring, and outer-ring roads; Shanghai-Nanjing highway; and Shanghai-Beijing highway), the uncertainty of road stock estimation was higher than that of other infrastructure. We made two assumptions to address information gaps for other roads: (i) The age composition of roads in 1980 was similar to that of residential buildings according to the urban housing survey in 1986,[32] which was 25% built before the 1960s, 15% built in the 1960s, and 60% built in the 1970s. (ii) Closer to the city center, the roads will be older. More details regarding our data sources and assumptions are listed in Table S3.

2.2. Data Rasterization and Spatial Material Flow Analysis. To facilitate the spatial analysis and policy discussion, point data on residential buildings and line data on transport networks were geographically transformed to raster data. The grid size of raster data should be determined based on the following two considerations:

- The efficiency of attribute data collection. Because of the huge number of residential communities in Shanghai (there were about 24 000 in 2010 according to the POI statistics), it is impossible to collect all the attributes information on each community from SouFun's Web site. As a compromise, we randomly picked a community sample in each grid cell that contains residential communities, collected its attributes from the SouFun's online database, and then assigned that information to the entire corresponding grid. The larger the size of a grid cell, the more residential community samples need to be collected.
- The accuracy of results. A suitable grid cell size should ensure both the accuracy of results and the efficiency of data collection. In this study, the grid cell size was determined as 500 m × 500 m. Within each grid that contains residential communities, the number of residential communities per grid cell varied from 1 to 13 with a mean number of 7. This largely improves the efficiency of data collection. Taking the data in 2010 for example, attributes of only 3235 communities (out of 23 822 communities) were extracted. Moreover, through the validation (see details in section 2.3), our results were proven to be reliable enough.

Based on the grid-level infrastructure database for the years 1980, 1990, 1995, 2000, 2005, and 2010, material stocks (MS) accumulated in different types of urban infrastructure in each year were estimated by multiplying the amount of remaining infrastructure at the end of the year by the material intensity of the infrastructure in its corresponding years of construction (eq 1).

$$\mathrm{MS}_{i,m}^{t} = \sum_{n} Q_{i,s,n}^{t} \times \mathrm{MI}_{i,s,m,n} \tag{1}$$

where $\mathrm{MS}_{i,m}^{t}$ is the stock of material m in infrastructure i at the end of year t. $Q_{i,s,n}^{t}$ is the quantity of infrastructure i with structure s and year of construction n. It could be the floor space in square meters (m^2) for residential buildings or kilometers (km) for transport networks. $\mathrm{MI}_{i,s,m,n}$ represents the material intensity, i.e. the amount of material m with structure s and year of construction n in infrastructure i, which is in units of kilogram per square meter or per kilometer (see Table S6).

A demolition rate was used for the estimation of material output flows (MOF) associated with infrastructure stock dynamics. As reported in many studies,[22,23] a logistic function has been proven simple but valid for the demolition curve of residential buildings.

$$D_{\mathrm{rb}}^{t} = \frac{1}{1 + \alpha \cdot \exp(-\beta \cdot (t - n))} \tag{2}$$

where D_{rb}^{t} is the demolition rate of residential buildings (rb) in year t. α and β are coefficients of the logistic function. $t - n$ is the years since construction. As suggested by Komatsu,[33] the average lifetime can be modeled as the length of time required for the number of buildings built in a given year to approach 50% of its original value. It is found that the mean lifespan of Shanghai's residential buildings is only 27 years (see Figure S1). The refurbishment and renovation of residential buildings is not considered because of its relatively small magnitude compared to the demolished amount and the lack of robust data.

Unlike residential buildings, it appears from the literature that the existing roads, railways, and subways in China seldom go out of service, but are maintained instead.[11] Because of the lack of empirical information especially at city scale, all the road layers are considered to be in maintenance, and a normal distribution function is used to represent the maintenance rate of transport infrastructure (trans) by assuming it equals the demolition rate, in which DEV is the standard deviation and AVG is the average lifespan. According to the design codes for roads,[34] railways,[35] and subways,[36] the designed service life are 20 years for highway and first-class roads, 15 years for second-class roads, and 100 years for railways and subways. However, the real lifespans are usually much shorter than expected because of natural (e.g., climate) and human (e.g., construction quality and maintenance) factors. The average lifetime (AVG) in our estimation is set as 10 years for highway and first-class roads, 8 years for second-class roads, and 30 years for railways and subways following the results of some empirical studies.[37,38] DEV is set as 30% of AVG.

$$D_{\mathrm{trans}}^{t} = \frac{1}{\mathrm{DEV}\sqrt{2\pi}} \int_{-\infty}^{t} \exp\left(-\frac{(t - \mathrm{AVG})^2}{2\mathrm{DEV}^2}\right) \mathrm{d}t \tag{3}$$

The material input flows (MIFs) into the infrastructure system were calculated as the difference between total material stocks at the end of the year and the remaining old stocks.

$$\mathrm{MIF}_{i,m}^{t} = \mathrm{MS}_{i,m}^{t} - \mathrm{MS}_{i,m}^{t-1} \times (1 - D_{i}^{t}) \tag{4}$$

2.3. Reliability Test and Result Validation. To test the reliability of our model's intermediate results, we aggregated the estimated floor space of residential buildings and the length of transport networks from the 500 m × 500 m grids to a district or city level and compared them with the official statistics published by the government.[26] It is found that the accuracy of our estimation is relatively high, with the errors in most years below 10% except that of highways in 1995 and the first-class (11.88%) and second-class (13.46%) roads in 1990 (see Tables S2 and S4). We also performed a validation of our final results with an independent study[39] that used a top-down

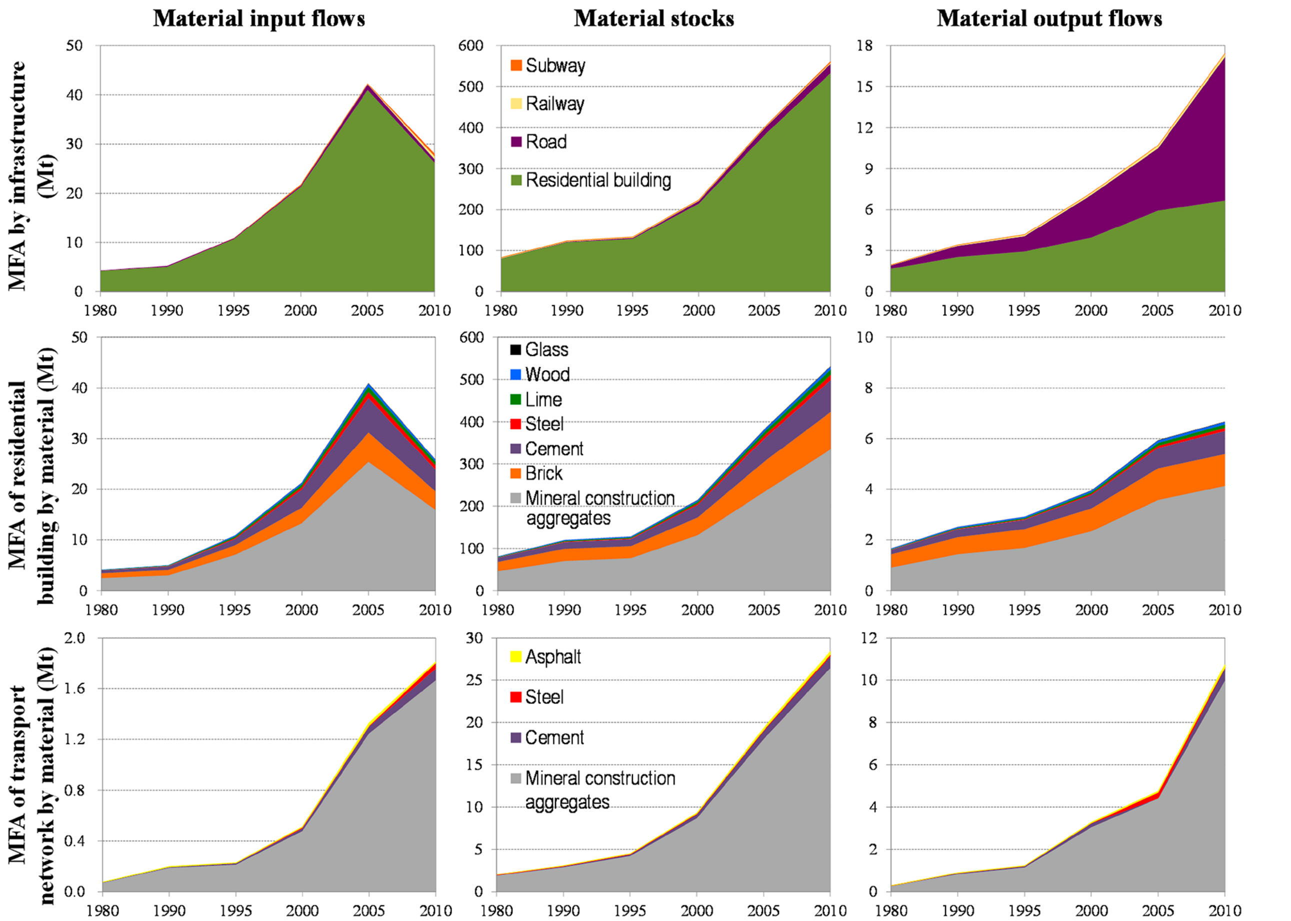

Figure 2. Material metabolism of urban infrastructure system 1980−2010.

material flow analysis method and a different data source to estimate the material stocks of the same types of infrastructure in Shanghai. By calculating the difference between ours and that independent study (as shown in Table S5), it is found that our estimates are very close to that study. Thus, we believe the proposed bottom-up approach for compiling data and estimating the material stocks and flows of infrastructure development in a city in a developing country is relatively reliable.

3. RESULTS AND DISCUSSION

3.1. Changes in Material Stocks and Flows over Time.

Figure 2 illustrates the temporal changes of material stocks and flows accompanying the infrastructure development in Shanghai. Between 1980 and 2010, in-use stocks have experienced first a steady growth during 1980−1995 (annual rate of 3%) to then an accelerated growth in 1995−2010 (annual rate of 10%; due to escalating economic growth and urbanization after the further reform and opening-up policy in the early 1990s, e.g., the development of Pudong New District). Since 1980, the total stocks increased by a factor of 7, reaching 561 million metric tons (Mt) in 2010, in which residential buildings were the largest material container (94.9%), followed by roads (4.2%), subways (0.5%), and railways (0.4%). The extension of transport networks has been given increasing attention, as their material stocks have grown 1.5 times faster than that of residential buildings, and their contribution to the total stocks also increased from 2.5% in 1980 to 5.1% in 2010. Differing from the changing pattern of the absolute amount of MS, per capita MS underwent a rapid growth before 2005 and slowed afterward, accompanying the continuous urbanization processes (Figure S2a,b). However, it is still hard to tell whether the per capita MS has reached saturation or not unless we could update the study period to the latest years.

Unlike the continuous increase of stocks, the input flows peaked at 42.3 Mt in 2005. It is mainly caused by the slowdown in the construction of residential buildings and roads in the late 2000s. The material inputs to buildings and roads accounted for over 96% of total inputs. This may be explained by two reasons. First, the global economic crisis since 2008 had negative effects on China's construction activity. The economy of Shanghai shifted gear from a high growth speed of 16.8% per annum in the last two decades to a medium-to-high speed of 9.3% since 2008.[26] As a result, the annual increment of investment on real estate and transport sectors also slowed from 15.4% between 2000 and 2008 to 9.7% between 2008 and 2010. Second, especially since 2005 the stepped-up control policies to cool the overheating housing market, such as the collection of land appreciation tax and the increasing down-payment ratio for house purchases, were another cause for the decline in newly built buildings.

The output flows from infrastructure systems increased steadily from 1.95 to 17.42 Mt in the last 30 years, of which the largest fraction was from residential buildings followed by roads, railways, and subways before 2005. While after 2005, the waste coming from roads exceeded that of residential buildings

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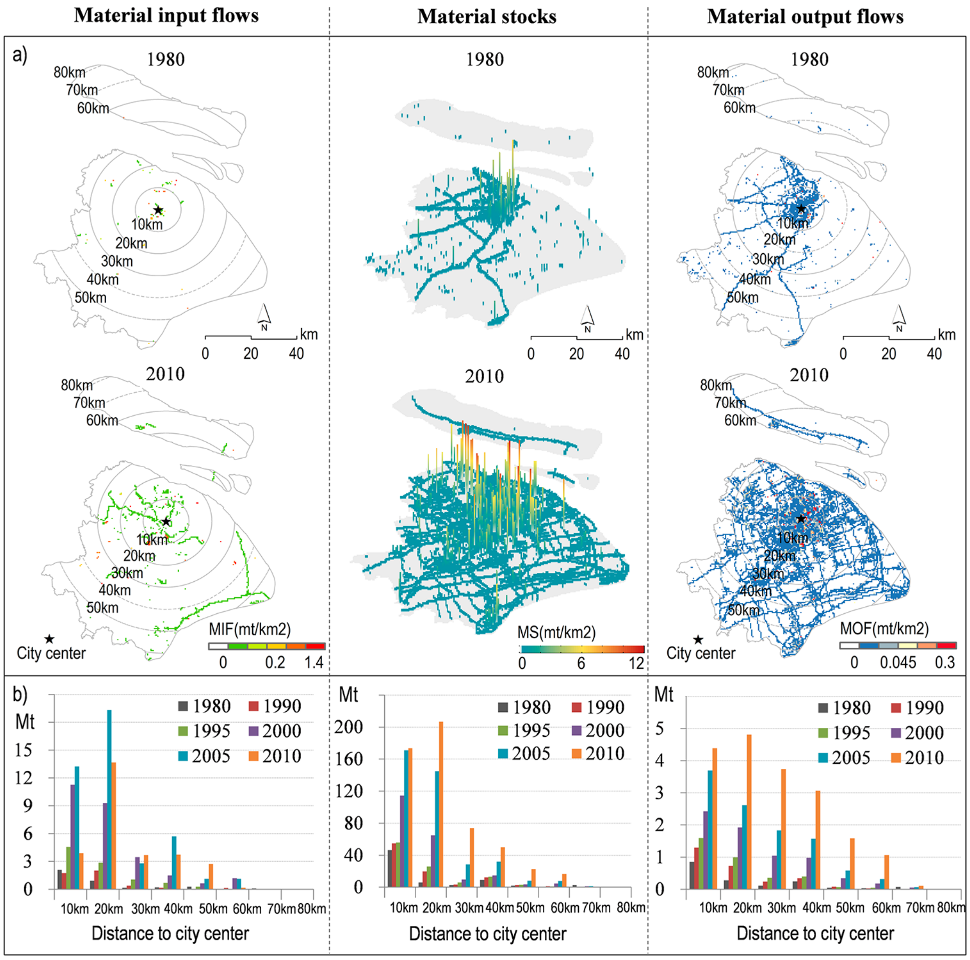

Figure 3. Spatial material metabolism of Shanghai's infrastructure: (a) distribution of material inflows, stocks, and outflows and (b) statistics by urban−rural distance classes (Mt = million tons; km^2 = square kilometers).

and became the biggest, which is mainly attributed to the short lifetime of roads.

Composition wise, mineral construction aggregates, brick, and cement are the three largest materials in the infrastructure metabolism, which accounted for 92−96% of MIF, 94−96% of MS, and 94−97% of MOF, respectively. Because of the growing demand for high-rise buildings and convenient and durable transport infrastructure, especially in densely populated megacities, a significant increase in those materials with high ecological footprint (such as cement, steel, and lime) can also be detected. Taking steel as an example, its annual growth rate in residential buildings was 10.6% for MIF, 11.1% for MS, and 9.4% for MOF, respectively. This growth in transport networks especially in subways was extremely significant (16.7% for MIF, 24.8% for MS, and 37.7% for MOF; see Figure S3). In total, the accumulation rate of steel in Shanghai's infrastructure (10.9% per annum) was even faster than China's average of 9.3% per annum.[40]

3.2. Spatial Patterns of Material Stocks and Flows. As illustrated in Figure 3, the MS of infrastructure has shown a pattern of growing outward and upward. The largest MS was found in the center (approximately the <10 km range according to the spatial distribution of population density) and peri-urban areas (approximately the 10−20 km range according to the spatial distribution of the population density), which together contained over 70% of the total MS of Shanghai. The suburbs within 10−60 km gradients witnessed the fastest growth of MS, with an annual rate around 9.9%, which was much faster than the city's average of 7%.

To reveal the MS growth more clearly, Figure 4 divides all grid cells into five classes according to the growth rate of MS. The city center was dominated by slow-growth class (accounting for 57% of total grids with MS variation) followed by newly built class (41%), which implies a trend toward saturation of MS in this area. In contrast, the suburbs (10−60 km) were dominated by newly built class of MS growth from 1980 to 2010, as 80%−92% of grids with MS variation was attributed to this class. It is also found that not all the materials grew in the same spatial pattern. Specifically, in the center area, except asphalt that has been growing most rapidly because of new road construction (e.g., inner-ring roads in the 1990s), the other seven types of materials demonstrated a slow growth trend. The fastest stock addition concentrated in the peri-urban area and declined along the urban−rural gradient, in which cement stock has been growing most rapidly as a result of new infrastructure construction, followed by steel and asphalt (see MS in Figures S4S−S11). Interestingly, when looking at the per capita MS changes in different urban−rural distance classes, the city center has witnessed a saturation of per capita MS with the turning point occurring in 2005. Other areas are still dominated by a growing trend of MS per capita (Figure S2c).

In the 1990s, China's housing market reform prompted the privatization of housing units that were previously owned by

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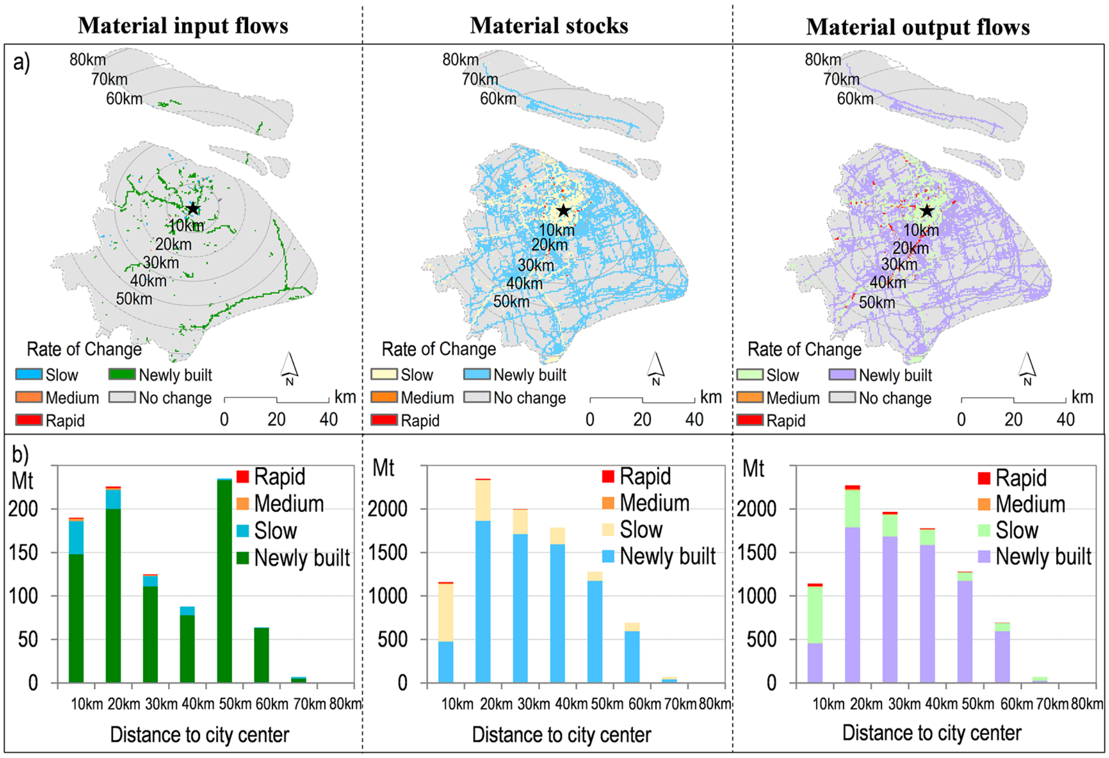

Figure 4. Spatial patterns of materials stock and flow variation in Shanghai's infrastructure. (a) Rate of change in stocks and flows from 1980 to 2010 according to their growth rate on the basis of natural breaks (Jenks) method. Using the software ArcGIS Desktop 10.1, the growth rates are divided into classes whose boundaries are set where there are relatively big jumps in the values.[41] (b) Number of grid cells with stock or flow variation in urban−rural distance classes.

the state. Meanwhile, the quick increase of income level and urbanization exerted a strong push on the demand for new dwellings. As such, new buildings and affiliated transport infrastructure were mainly constructed in the suburbs because of the soaring housing prices and limited land availability in the center area. From the perspective of input flows, our result does reflect such a spatial trend (see MIF in Figure 3). Before 1990, over 55% of material input was into the center area (<10 km). From 1990 to 2010, the suburban areas (10−60 km) absorbed a dominant amount of materials input, with their fraction rising from 61% to 86%. Though the input flows peaked in 2005 and declined afterward in most parts of Shanghai, the suburbs between 10 and 60 km still registered a 9.5% annual growth in materials input, which is much faster than the 2% annual growth in the center. As shown in Figure 4, though the slow-growth class of MIF increased relatively significantly in the city center (accounting for 20% of all MIF variation), the newly built class of materials input due to urban sprawl was the principal source of MIF increase in Shanghai during the past three decades. It is particularly distinct in the suburbs (10−60 km) where the share of the newly built class accounted for 88%−99% of all MIF variation. The input materials, which are more intensively used in residential buildings (e.g., cement, lime, and glass), showed a rapid growth trend in the peri-urban area. The materials that are used more in roads and railways (e.g., asphalt, steel, and wood) were found to increase significantly in suburban areas especially in the 40−50 km range. The construction of express loop highways and railways in southeast Shanghai since the 2000s was the main reason (see MIF in Figures S4S−S11).

For the demolition waste generation (see MOF in Figure 3), the amount within each urban−rural gradient has been increasing. Over 50% of waste was located within the 0−20 km range because of the large quantity of MS accumulated in this area, in which over 2/3 of the waste was from residential buildings. However, the outer suburbs in the 20−30 and 40−60 km ranges registered the fastest annual growth rate of 12%, in which about 60% and 80% of wastes were from roads. The short lifetime of roads that results in the frequent replacement of road materials was the main reason for the fastest waste generation in the outer suburban areas. Because the spatial pattern of MS growth determines that of MOF, the newly built class was the dominant class of MOF growth in suburban areas, while slow-growth was the main class in the city center (see MOF in Figure 4). In addition, the generation of most waste materials in the city center illustrated a slow-growth trend except for asphalt and brick. In the suburbs, demolition waste flows of all materials were largely from infrastructure constructed after 1980, in which cement, asphalt, and steel were the most rapidly increasing materials (see MOF in Figures S4−S11).

3.3. Transferability and Uncertainties of Our Results.

Data availability and quality are widely recognized as the major obstacles for the understanding of city-scaled material stocks and flows, especially concerning their spatial and temporal patterns. The recent development of big data and online database (e.g., those attributed to data of residential buildings from SouFun), as shown in our case study, opens a new window for addressing this gap. As SouFun is a national-level company with business in almost all Chinese cities, it should be feasible to collect similar data for other Chinese cities for a better understanding of their spatiotemporal dynamics of material stocks and flows in urban infrastructure development. Other similar databases and new types of big data (e.g., point

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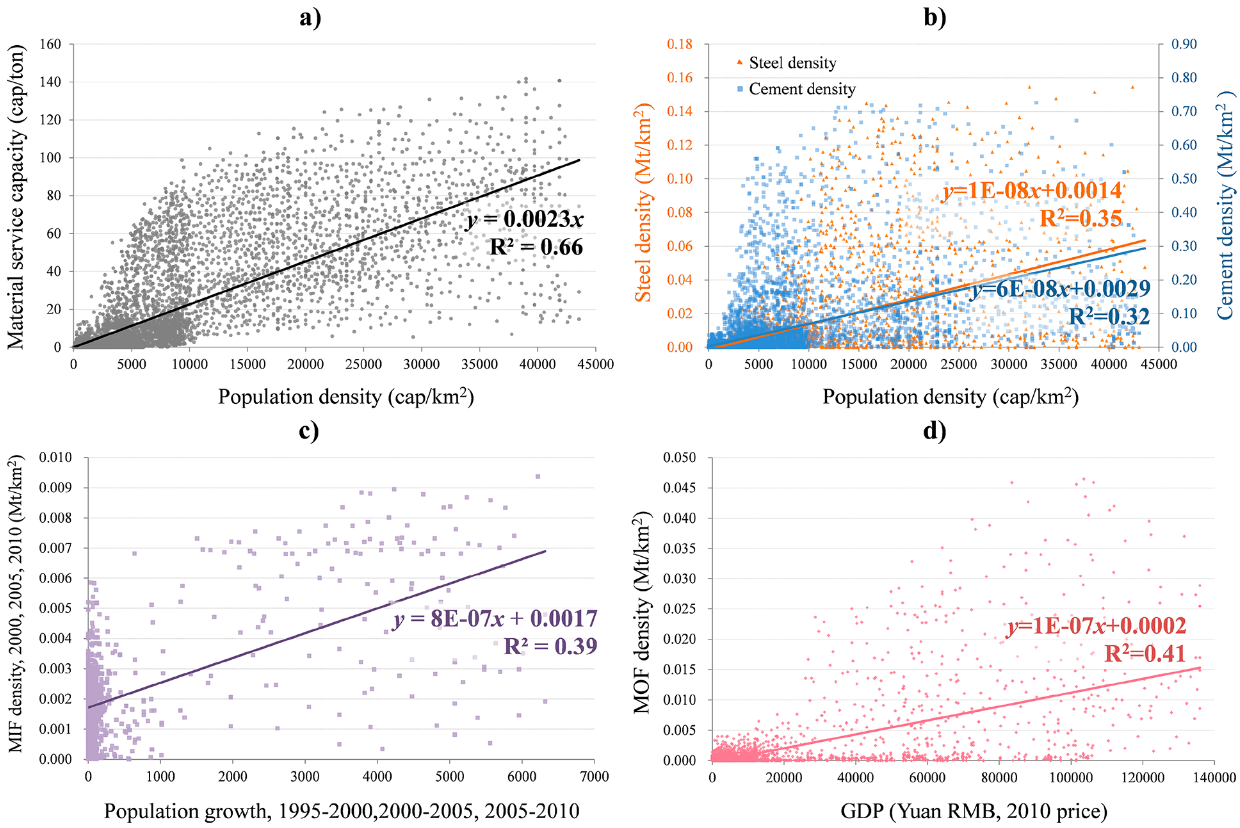

Figure 5. Correlation between materials stocks and flows and socioeconomic development: (a) population density vs population per material stocks, (b) population density vs steel and cement density, (c) material input flows vs population growth, and (d) demolition waste vs GDP. All the data are calculated from the 500 m × 500 m spatial grids. Grid-scaled population and GDP data for 1995, 2000, 2005, and 2010 are provided by the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences.[51] The intercept term of the graph in panel a is intentionally set as 0 as when population density is 0 the population served by materials should also be 0.

of interest and StreetView map) for cities in other countries may also be explored in a similar approach.

However, several limitations remain in our analysis. First, we did not include all types of urban infrastructure, such as nonresidential buildings, water and sewage pipelines, and power plants, and thus our results provide a low estimate. As reported in recent MFA studies on the infrastructure system of China or Chinese megacities, the material stocks of nonresidential buildings and water and sewage networks were 50%−80% and 10−30%, respectively, of that of residential buildings.[9,39,40] This indicates that the magnitude of total material stocks of urban infrastructure should be at least 1.5−2 times larger than the current estimate if we take this missing infrastructure into consideration. Further data on the amount, spatial distribution, and attributes of these types of infrastructure should be collected for a full understanding. Second, our data on the amount and material composition of infrastructure bear uncertainties as well. Specifically, though data on the amount of infrastructure calibrated from spatial grids are proven to be relatively accurate when compared to the official statistics, the attributes (especially the year of construction) and lifetime of infrastructure obtained through our bottom-up sampling method and the assumption of demolition curve cannot be verified for the entire city because of lack of official information. In addition, material intensity from literature and design codes may not be representative as they might be applicable to the national average but not to the specific cities. For example, the external walls of residential buildings in northern China are usually built thicker than those in the south even if the floor space is the same.[42] Through the sensitivity analysis of the material input flows, stocks, and output flows to different material intensity while keeping other parameters constant, it is found that mineral construction aggregates, brick, and cement are the dominant materials, for which every 10% variation will contribute to a 6.25%, 1.68%, and 1.45% change of total stocks and flows, respectively (see Figures S12−S14). More bottom-up field surveys regarding the attributes of infrastructure are needed to fill these information gaps.

3.4. Policy Implications for Sustainable Infrastructure Development. The GIS-MFA integrated method we developed enables the characterization of the spatiotemporal patterns of material metabolism of infrastructure development at a relatively high spatial resolution. More importantly, it facilitates the investigation of the correlation between material utilization, socioeconomic development, and environmental impact on a more refined level so that effective policies could be derived for sustainable infrastructure planning and environmental management. Notably, some coefficients of determination shown in Figure 5 are not so high, which may suggest some other factors play important roles in affecting the change of material stocks and flows. Further investigation of the driving factors is needed with the support of more detailed data, especially at a refined spatial scale.

First, our results can be used to reveal more in-depth relationships between city compactness, material service

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capacity, and environmental impacts. As shown in Figure 5a, city compactness (measured by population density) is correlated significantly with material service capacity (measured by population per unit of material stocks). In other words, stocks in the denser areas of cities (e.g., city center) can provide services to more people, which may also reduce energy use and emissions in the operation of these infrastructure (e.g., heating energy use). However, a trade-off is that the construction structures of residential buildings, roads, and subways in the densely populated areas were composed dominantly of reinforced-concrete and steel-frame types so that they can be vertically strong and durable (Figure 5b). These materials are often associated with high environmental footprint and consequently pose great challenges to the environment because of the lock-in effects of material stocks on energy consumption and carbon emission pathways throughout their lifetime, which has been highlighted in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC).[43]

Second, our results could better inform future materials demand and waste generation. As shown in Figure 5c,d, the correlation between the past and current materials stocks and flows and the socioeconomic drivers (e.g., population and GDP) can be better understood at a refined level. Urbanization is seen as the primary development strategy in China. If the current trend continues, urban population is expected to increase by over 100 million until 2020 according to the National New-type Urbanization Plan (2014−2020). Assuming the correlation obtained from our case of Shanghai (Figure 5c) is applicable to all Chinese cities, and that the urban built-up area remains the same as in 2014, at least 36 billion tons of construction materials will be needed until 2020 to provide services to those people moving to urban areas. Remarkably, such a huge amount of materials input will be 18 times larger than the total inputs of nonmetallic construction minerals of residential buildings, roads, and railways of 25 EU countries in 2009.[44] In a resource- and climate-constrained era, such a huge demand for materials will definitely aggravate environmental burdens and hamper the climate change mitigation of China if all the materials are from virgin resources.[2] Alternatively, recycling and reuse of construction materials would have many environmental benefits, such as saving energy compared with the production of primary materials.[45,46] As such, implementing a circular economy approach and increasing the recycling and reuse rate of demolition waste are necessary countermeasures for relieving the resource burden and improving material efficiency.[47] The current recycling rate of construction and demolition waste is extremely low in China (less than 5% as a national average[48] and less than 20% for Shanghai[49]), which calls for special attention on recycling. Moreover, because the lifetime of infrastructure is a key parameter that determines both the waste flows and input flows, a significant reduction of environmental impacts is expected if the average lifespan of infrastructure can be extended through proper design and management. Our results demonstrate that if the lifetime of residential buildings can be extended from 27 to 50 years, and the replacement interval of transport networks can also be extended to their designed service lifetime during the studied period, the cumulative saving of material inputs and reduction of demolition wastes would be 50 and 80 Mt respectively, which equals 3% and 12% of corresponding material inputs and waste outputs in 25 EU countries in 2009.[44] As pointed out by some researchers, the external factors (e.g., the change of urban planning) are more important reasons than internal ones (e.g., construction structure) behind the short lifespan of infrastructure in China.[50] Potential improvements could be achieved by increasing the construction quality, strengthening the monitoring and maintenance of in-use infrastructure, and establishing a sustainable urban development plan. Moreover, our approach can aid strategic planning in waste management. Our high spatial resolution maps with both the quantity and composition of waste flows could inform the municipal government and relevant companies in their decision-making on the location, capacity, cost allocation, and technology choice for construction and demolition waste collection and disposal.

Third, despite several limitations, this study demonstrates the feasibility and implications of analyzing material stocks and flows at a city level with high spatial resolution. Such a method can be applied to other rapidly urbanizing cities and integrated with environmental impact assessment models to reveal the general patterns of urbanization, material use, and corresponding environmental consequences. Potential options include combining our GIS−MFA integrated method with life cycle assessment (LCA) studies of building and transportation sectors to analyze both the direct (i.e., operation of infrastructure) and indirect (i.e., construction, maintenance, refurbishment and renovation, and demolition of infrastructure) impacts of urban infrastructure development on material use, waste generation, energy consumption, carbon emissions, and water use.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.8b03111.

Material intensity/composition, data sources and validation, demolition rate estimates, spatial patterns for individual materials, and uncertainty analysis (PDF)

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