Changes in Reticular River Network under Rapid Urbanization: A Case of Pudong New Area, Shanghai

Yuqing Shi 1, Yang Yao 2, Jun Zhao 1,*, Xiangying Li 1, Jia Yu 3 and Guangren Qian 1

Abstract: Large quantity of rivers have disappeared during rapid urbanization in China’s Yangtze River Delta, and it is difficult to define the changes in the river network owing to its high dense and complex reticular structure. Shanghai’s Pudong New Area (SPNA) is a typical area of rapid urbanization in the delta. A Comprehensive River-network Indicator System (CRIS), including quantity and area, geomorphologic structure, and landscape connectivity indicators, was established to characterize the changes in the dense reticular river network in SPNA from 1965 to 2010. The percentage of urban area rapidly increased from 22.52% to 59.49% in SPNA, whereas that of water surface (W_p) decreased from 10.57% to 7.23% during the same period. The changes in river network displayed a clear spatial gradient, and the closer the functional area is to the city center, the earlier and faster the changes in the rivers. CRIS obviously changed when the percentage of built-up area increased from 10% to 30%; however, the CRIS changed more gently when the percentage exceeded 30%. Among the three sub-indicators of CRIS, quantity and area strongly corresponded to urbanization stages, geomorphologic structure was most sensitive to urbanization, and landscape connectivity accurately captured the threshold phenomena in the change in reticular river network.

Keywords: reticular river network; comprehensive river-network indicator; functional area; rapid urbanization

1. Introduction

A reticular river network often appears on alluvial plains near estuaries, such as the Yangtze Delta in China, Mississippi Delta in the United States, and Ganges Delta in India. The most obvious feature of such a network is its dense river pattern and complex reticular structure [1]. Several rivers have disappeared during rapid urbanization in such river deltas, and the reticular structure of the river network has greatly changed [1–7]. In recent decades, rapid urbanization in China has greatly impacted river networks, especially after the 1980s. This typically occurred in regions like the Yangtze Delta in East China, which is greatly urbanized and characterized by a complex reticular river network [8].

However, previous studies were usually limited to traditional indicators for investigating changes in watershed river systems over short periods, and dendritic river systems were mostly reported. Traditional indicators may be divided into two categories: quantitative category, such as water area percentage (W_p), river density (R_d), and river frequency (R_f), and geomorphologic category such as branch ratio (R_b). These indicators have been widely used in research on river hydrology and watershed geomorphology for decades [9–13].

It is difficult to characterize the features of reticular river networks using traditional indicators [14,15] owing to its vague orders and special reticular structure. One of the problems is that indicators like R_b may not be usable, because it is difficult to distinguish mainstreams from tributaries, and there is even no appropriate stream ordering system...
for reticular network. Another problem is that there is no special indicator to detect the threshold of the change in river network structure; that is, whether the river network changes from reticular to non-reticular.

Regarding the first problem, the traditional river ordering system may not be applicable for reticular network [16]; however, in practice, a dense river network is often classified into four orders by the local water administration in Yangtze Delta, China. The lowest order is that of the village, then town, district, and city (the highest) [17]. Rivers of city and district order are often regarded as mainstreams, and their quantities may be several to hundreds. Those of town and village order are tributaries, numbering thousands or even tens of thousands.

This ordering system has existed for nearly 30 years in the Yangtze Delta, in cities such as Shanghai, Ningbo, Wuxi, and Suzhou but has seldom been used for studying reticular river network [18–20]. The most important reason may be that data could not be obtained from local water administration. Therefore, some new indicators, such as the river development coefficient ($R_z$), which is defined as the ratio of total length of tributaries to total length of mainstreams [21], is used in this study to characterize the structure of reticular rivers.

Besides the river ordering system and indicators for describing changes in river network structure, there is another challenge that is often neglected. A study area is often taken as the entire city while determining river network change in a city, and any difference among functional areas in the city is ignored, and in functional areas, such as industrial, residential, commercial, or protected area, river networks can have different change processes.

River network changes have a significant impact on urban water security, especially in the high-density river network areas of the Yangtze River Delta in China. Shanghai’s Pudong New Area (SPNA) is a typical representative of the urbanization in China in the past 30 years. It is located at the easternmost edge of the Yangtze River Delta. The river network in SPNA shows a typical complex reticular structure. Therefore, this study aimed to investigate the impact of urbanization on the river network during the period from 1965 to 2010, analyze the sensitivity of different river network indicators to urbanization and the differences in the performance of these indicators at different stages of urbanization. It is attempted to provide a reference for the protection of river networks in urbanized areas, revealing the grade of rivers that is more important to protect and at what stage of urbanization. Therefore, special attention should be paid to river network protection.

The first purpose of this study was to propose the use of Comprehensive River-network Indicator System (CRIS) for analyzing the characteristics of river network change before and after SPNA’s rapid urbanization, according to the local river ordering system. The second was to explore the differences of the significance and sensitivity between the sub-indicators of CRIS. Finally, spatial variations of river network change were detected among the different functional areas in SPNA, and some key indicators were proposed to protect the river network during the next round of urbanization.

2. Materials and Methods
2.1. Study Area

The SPNA study area spans 569 km², covered by six functional areas: Lujiazui Financial and Trading Zone (LJZ), Jinqiao Export Processing Zone (JQ), Zhangjiang High-Tech Park (ZJ), Waigaoqiao Free Trade Zone (WGQ), Chuansha Zone (CS), and Sanlin World Expo Zone (SL) (Figure 1). These areas differed in their development targets, which resulted in varying urbanization levels. LJZ is part of central Shanghai and has the highest development level, whereas CS has the lowest, with agriculture as its primary industry. JQ, ZJ, and WGQ are national industrial parks, and SL is in a source-water protection area of the city along the upper Huangpu River.
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Figure 1. Sketch map of Shanghai’s Pudong New Area (SPNA) and its six functional areas and flow chart of this study.

2.2. Land Use and River Data and River Ordering System

Remote sensing data of the land use and river network were obtained for six years: 1965, 1989, 1994, 2000, 2003, and 2010. The data from 1965 to 2000 were from airborne remote sensing, with image resolution 2.0 m. The data from 2003 to 2010 were from the SPOT-5 satellite, with resolution 2.5 m. Although there were differences between these data, their spatial resolutions met the requirements of river interpretation, since river widths are typically greater than 3 m in Shanghai.

Several steps were taken to interpret the river data, such as geometric rectification, spectral processing, image stitching, coordinate positioning, and water body enhancement, using ESRI ArcGIS 10.2 software, due to the inevitable errors of interpretation (for example, cloud-shaded rivers or river surfaces are covered by pollutants or waste). To improve interpretation precision, a field survey was conducted, and 50 locations were selected to ascertain the characteristics of such errors. This was followed by rectifications of the interpreted data. The remote sensing data were interpreted by the Key Lab of Geographical Information Science Ministry of Education, China, which is also a branch of East China Normal University.

2.3. Methods of CRIS

According to the Shanghai Census System of Water Resources Information, all rivers were categorized into four orders: village, town, district, and city. Rivers of city and district order were regarded as mainstreams in the network, while those of village and town order were regarded as tributaries.

The CRIS used in this study included three indicators: quantity and area, geomorphologic structure, and landscape connectivity indicators, and six sub-indicators, which are shown in Table 1. It should be stressed that the indicators of quantity and area (including $W_p$, $R_d$, and $R_f$) are all traditional and widely used, whereas those of geomorphologic structure (including $R_z$ and $R_b$) and landscape connectivity ($\beta$) were purposely developed for analysis of the reticular river network in SPNA.
Table 1. Interpretation of the Comprehensive River-network Indicator System (CRIS).

| Indicator                      | Sub-Indicator          | Formula                                                                 | Unit       | Physical Interpretation                                                                 |
|-------------------------------|------------------------|-------------------------------------------------------------------------|------------|-----------------------------------------------------------------------------------------|
| Quantity and area of rivers   | Water area percentage (Wp) | Wp = Rs/A × 100%                                                       | %          | Ratio of total river area vs. regional area                                               |
|                               | River density (Rd)      | Rd = L/A                                                                | km/km²     | River length per unit regional area, reflecting river length development                  |
|                               | River frequency (Rf)    | Rf = N/A                                                                | quantity/km² | River quantity per unit regional area, reflecting number of river development             |
| Geomorphologic structure      | River development (Rd)  | Rd = Ld/Lm                                                              | km/km      | Ratio of length of tributaries to length of main river, reflecting river length development of tributaries in river network |
|                               | Average branch ratio (Rb) | Rb = Ns/Ns+1                                                           | quantity/quantity | Ratio of quantity of xth tributaries to quantity of x + 1th tributaries, reflecting branching ability from higher to lower-level rivers |
| Landscape connectivity        | Connectivity ratio (β)  | β = L/N                                                                | /          | Ratio of quantity of river chains in river network to quantity of vertices                |

The connectivity indicator derived from graphic theory can be used to define the connectivity of the network, and the most popular indicator may be the connectivity ratio (often used as β in literatures), which is defined as the ratio of the quantity of river chains to the quantity of vertices (Figure 2). This indicator has been commonly used in landscape ecology but has not been applied to the study of river network change.

Although there are geomorphological indicators, such as the branch ratio (Rb), the reticular structure in the river network area is very complicated, and the genetic mechanism of river branching and the ordering system of the municipal river management system are not clear enough. Therefore, the river network development indicator Rz was proposed to simplify the concept of branching by dividing the total river length (municipal-, district-, town- and village-order) by the main stream channel length (city- and district-order). The larger the Rz, the higher the level of river network development.
Table 1 and Figure 2 show the schematic diagram and algorithm of river network connectivity.

$R_x$ and $\beta$ are proposed in this study, especially for the reticular river network. $R_x$ is to describe how the quantity of tributaries developed compared to the mainstreams in the network, and $\beta$ is to analyze how many circuits existed in the network. The more circuits exist, the more powerful the hydrodynamic of the rivers. The threshold is when there is only one circuit in the network ($\beta = 1$), and when $\beta < 1$, there will be no circuit (Figure 2). Using the CRIS, we analyzed the change in the reticular river network (Table 1) and the sensitivity of various indicators in response to urbanization. The spatial variation of river network change in different functional areas was also evaluated.

3. Results and Analysis

3.1. Overall Trends of Urbanization and Change in River-Network in SPNA

The land use change in SPNA for 45 years from 1965 to 2010 is shown in Figure 3. It can be seen that the change was not significant from 1965 to 1989, because urbanization mainly focused on the area west to Huangpu River. After 1989, the rapid development of six functional areas led to great changes in the land use pattern of SPNA. Among the different land use types, the percentage of urban built-up area (including industrial land, road and traffic, residential, public buildings, and urban green space) rapidly increased from 22.52% to 59.49%. However, those of agricultural and water decreased from 68.12% to 27.47% and 10.57% to 7.23%, respectively.

![Figure 3. Change in land use and river network in Shanghai’s Pudong New Area (SPNA) (1965–2010). (1) Land use change of SPNA, (2) Change of river network in SPNA.](image)

Changes in the river network in SPNA for four decades are shown in Figure 3. During the entire period from 1964 to 2010, the quantity of rivers rapidly declined from 13,000 to 7800. The period was divided into three smaller periods, according to river extinction rates: the first was the stable (1965–1989), the second was the rapidly disappearing (1989–2000), and the last was the slowly disappearing (2000–2010). These periods are consistent with corresponding ones of rapid urbanization in SPNA (Figure 3).

In total, the river network underwent extreme extinction for four decades, except that CS maintained a near-natural structure with high dense river network. CS is furthest from LJZ (the city center). The river network change showed a clear spatial gradient from west to east: the closer the functional area was to LJZ, the earlier and faster the river network changed.

3.2. Extinction of Rivers of Different Orders

Change in length and quantity of rivers of various orders are shown in Figure 4. Disappeared rivers were mostly those of village and town order; total length for these orders...
that the disappearance of tributaries is the primary reason behind the simplification of the reticular structure of the river network. The network inside the Outer Ring Road (excluding CS) changed significantly from reticular, with large numbers of mainstreams and tributaries, to a simpler structure with only mainstreams.

Change in total river length and quantity of rivers in different orders.

3.3. Change in River Network at Functional Areas

Figure 5 shows changes in CRIS indicators in the six functional areas from 1965 to 2010 and reveals a significant decrease in each indicator in all functional areas. LJZ underwent the greatest change, while CS changed slightly relative to other five zones. Considering the most typical indicators, among the sub-indicators of quantity and area, the change in $W_p$ was LJZ $>$ JQ $>$ ZJ $>$ WGQ $>$ CS $>$ SL. This corresponded well with the difference in development year between the six functional areas. Changes in $W_p$ in LJZ and JQ were 43.23% and 39.96%, but only 19.06% and 13.35% in CS and SL, respectively. Among the sub-indicators of geomorphologic structure, the change in the river development sub-indicator $R_z$ was LJZ $>$ WGQ $>$ SL $>$ JQ $>$ ZJ $>$ CS, much different than that of $W_p$. The change in $R_z$ in LJZ was most notable (97.5%), whereas that in CS was 54.71%.

Three periods of river network change in SPNA in recent decades (left) and comparison of the indicator change at six functional areas (right).
4. Discussions

4.1. Sensitivity of Sub-Indicators to Urbanization

River network indicators respond differently to urbanization. Some indicators change drastically and are very sensitive to urbanization process, whereas others change more slowly and show weaker sensitivity.

Table 2 shows that all quantity, area, and geomorphologic structure indicators in CRIS changed notably over the past 45 years. Geomorphologic structure changed most rapidly with a range exceeding 50%. Landscape connectivity changed much slower than all the other indicators. Thus, it appears that geomorphologic structure is more sensitive to river network change.

Table 2. Change in the Comprehensive River-network Indicator System (CRIS) indicators in Shanghai’s Pudong New Area (SPNA) (1965–2010).

| Year | Quantitative and Area | Geomorphologic Structure | Landscape Connectivity |
|------|-----------------------|--------------------------|-----------------------|
|      | W_p | R_d | R_l | R_b | R_z | β     |                      |
| 1965 | 10.57 | 6.99 | 25.94 | 72.22 | 14.61 | 1.11 |
| 1989 | 10.12 | 6.23 | 24.61 | 53.42 | 8.59  | 1.05 |
| 1994 | 8.65  | 4.74 | 17.09 | 42.26 | 6.30  | 1.02 |
| 2000 | 7.99  | 4.01 | 16.25 | 38.85 | 5.34  | 0.98 |
| 2003 | 7.40  | 3.70 | 16.11 | 36.20 | 5.05  | 0.96 |
| 2010 | 7.23  | 3.45 | 14.47 | 32.54 | 4.53  | 0.96 |
| Change | 31.60% | 50.64% | 44.22% | 54.94% | 68.99% | 13.51% |

Among the sub-indicators of quantity and area, W_p changed less, while R_d greatly changed, indicating that the impact on river length was more obvious than area. For landscape connectivity, β tended to approach the threshold β = 1 after 1994, showing that the river network was being transformed from a complex reticular structure to a simpler structure.

4.2. Relationship between River Network Change and Urbanization

The current status of river networks in six functional areas is shown in Table 3. Due to locations, development targets, and land-use patterns, functional areas had different urbanization levels and river network features. LJZ, a highly developed central area of Shanghai, displayed a reticular river network that comprises some mainstreams, while CS has a near-natural reticular river network with dense tributaries. Correlation analysis on land uses and CRIS indicators in 2010 in six functional zones indicates that industrial land and public buildings were negatively related to river network indicators, whereas agricultural land was positively related (Table 4).

Table 3. Variations in river network in six functional areas.

| Functional Area | Urbanization Level | Urban Function | Dominant Land Use | Percentage of Rivers of Village Order |
|-----------------|--------------------|----------------|-------------------|--------------------------------------|
| CS              | Lowest             | Entertainment (Disney), residential | agricultural, residential | 74.08% |
| ZJ              | Medium             | National industrial park, Residential | industrial, residential | 66.15% |
Table 3. Cont.

| Functional Area | Urbanization Level | Urban Function | Dominant Land Use | Percentage of Rivers of Village Order |
|-----------------|--------------------|----------------|------------------|--------------------------------------|
| JQ              | Medium             | National industrial park, Residential | industrial, residential | 73.50% |
| WGQ             | Medium             | World largest port | industrial, agricultural | 41.28% |
| SL              | Medium             | Residential | residential, agricultural | 50.64% |
| LJZ             | Highest            | Central Business District | residential, public building | 6.69% |

Table 4. Pearson correlation analysis of the Comprehensive River-network Indicator System (CRIS) and land use.

| Indicator | Industrial | Road | Agricultural | Public | Residential |
|-----------|------------|------|--------------|--------|-------------|
| $W_p$     | -0.709 ** | -0.388 * | 0.748 ** | -0.829 ** | -0.507 ** |
|           | 0.000      | 0.019 | 0.000        | 0.000  | 0.002       |
| $R_d$     | -0.815 ** | -0.585 ** | 0.865 ** | -0.784 ** | -0.388 * |
|           | 0.000      | 0.000 | 0.000        | 0.000  | 0.020       |
| $R_f$     | -0.757 ** | -0.638 ** | 0.827 ** | -0.644 ** | -0.261     |
|           | 0.000      | 0.000 | 0.000        | 0.000  | 0.125       |
| $R_z$     | -0.690 ** | -0.488 ** | 0.711 ** | -0.750 ** | -0.411 * |
|           | 0.000      | 0.003 | 0.000        | 0.000  | 0.013       |
| $R_b$     | -0.803 ** | -0.524 ** | 0.825 ** | -0.706 ** | -0.385 * |
|           | 0.000      | 0.001 | 0.000        | 0.000  | 0.020       |
| $\beta$   | -0.821 ** | -0.624 ** | 0.855 ** | -0.606 * | -0.445 * |
|           | 0.007      | 0.004 | 0.010        | 0.012  | 0.020       |

** Significant at $p = 0.01$; * Significant at $p = 0.05$.

Figure 6 illustrates notable changes in indicators of CRIS. Percentage built-up area increased from 10% to 30%, implying that in this stage of urbanization, river network would be significantly affected, especially the $R_d$ and $R_f$ indicators, which decreased by 65% and 50%, respectively. The decrease in $R_d$ implies that a large amount of lower order rivers had been landfilled during urbanization, and the disappearance of these rivers resulted in simplified network. However, indicators of CRIS changed slowly when percentage built-up area increased beyond 30% and then became stable when it reached 60%, indicating that river network structure would no longer be affected by urbanization.

The development of six functional areas has a chronological order, but within similar urbanization stage (a certain interval of the built-up area percentage). Identical changes occurred for the river network indicators in different functional areas, indicating that humans treated the rivers in a similar way at each stage of urbanization. In terms of the changing trends of different indicators, when the percentage built-up area was between 10–30%, $R_p$, $R_z$, and $R_b$ changed fast, and when the percent built-up area was greater than 30%, $R_c$ changed slowly.
Figure 6. Changes in sub-indicators of Comprehensive River-network Indicator System (CRIS) with increasing urbanization level in Shanghai’s Pudong New Area (SPNA).

4.3. Urban Hydrological Response to River Network Change

Storage capacity of river channels has been greatly impaired owing to the dramatic extinction of rivers. Therefore, water safety issues, with regards to challenges to urban drainage, must be handled.

The relationship between the drainage modulus of pumping stations and river network indicator $R_d$ in SPNA is presented in Table 5. In the three urban sections separated by the Inner Ring Road and Outer Ring Road, the drainage modulus of pumping stations is clearly negatively related with $R_d$. It shows that an $R_d$ decrease of 1 km/km$^2$ increases the drainage modulus by 1.2 m$^3$/S·km$^2$.

Table 5. Relationships between drainage modulus of pumping stations and $R_d$ in different urbanization sections divided by Inner and Outer Ring Roads in Shanghai’s Pudong New Area (SPNA).

| Sub-Area                  | Area (km$^2$) | Quantity of Pumping Stations | Catchment Area (km$^2$) | Drainage Modulus of Pumping Station (m$^3$/s·km$^2$) | $R_d$ (km/km$^2$) |
|---------------------------|---------------|------------------------------|-------------------------|-----------------------------------------------------|------------------|
| Inside Inner Ring         | 30            | 10                           | 29.69                   | 5.80                                                | 0.47             |
| Between Inner and Outer   | 275           | 71                           | 217.46                  | 2.06                                                | 1.96             |
| Ring                      | 261           | 17                           | 58.74                   | 0.24                                                | 4.78             |
4.4. Limitations and Follow-Up Studies

The river network structure in SPNA is very complex, and it is difficult to order the rivers according to the Horton law of traditional river system except by the scheme of the Shanghai River Management System. In this scheme, even rivers have the same length and the hydrological and social functions of rivers in city centers are more important than those of rivers in rural areas, owing to the geographical difference; therefore, they were assigned with a higher order. There are also very common situations in which a river crosses multiple rivers; thus, how to judge the beginning and end of a river becomes a challenge. The ordering system of rivers in the reticular network is still a scientific problem that require further study for elucidation in the field of hydrology.

In addition, this study analyzed the impact of urbanization of SPNA on river network indicators for the past 45 years; however, the hydrological and environmental response of river network changes, such as the obstruction of river connectivity, should be paid attention to, to intensify regional flood and challenge drainage system. Blocking and landfilling of rivers also reduced the capacity of the river network.

In the future, based on long-term series of hydrological data, the impact of river-network changes on river flow should be studied, and special attention should be given to flood and drainage under heavy rainfall conditions. However, urban hydrological models such as MIKE Urban can be used to simulate hydrological process under different river network structure scenarios and under different rain conditions. Attention should also be paid to distinguishing the influence of river network changes, land use changes, river sluices, and other factors on hydrological process. Therefore, more targeted policy implications should be made for river network protection.

5. Conclusions

Taking SPNA as a case, this study investigated the impact of urbanization on river network during the period from 1965 to 2010, analyzed the sensitivity of different river network indicators to urbanization and the differences in the performance of these indicators at different stages of urbanization and functional area scale. The study attempted to provide references for the protection of river networks in urbanized areas. The grade of rivers that is more necessary to protect and the stage of urbanization require special attention for river network protection.

We proposed the use of CRIS, including quantity and area, geomorphologic structure, and landscape connectivity indicators, to analyze spatiotemporal variation of the reticular river network change in SPNA, which is one of the most rapid urbanization areas in China. With some limitations, the following conclusions are made.

i. The CRIS is useful for demonstrating the change in reticular river network. Among the three types of indicators, quantity and area correspond well to urbanization, geomorphologic structure is most sensitive to urbanization, and landscape connectivity may be a key indicator for determining critical changes in river structure. The impact of urbanization on river networks may be similar in the same urbanization period of functional areas, and when the urbanization level was lower than 30%, the impact was most visible.

ii. The disappearance of tributaries is the reason for extinction and simplification of river network. In addition, the differentiation of development targets of the six functional areas, including industrialization, urbanization and source-water reservation, caused varying impacts on river networks. This resulted in a clear spatial gradient change from west to east in the simplicity of the river network [22].

iii. The analysis of landscape connectivity showed that the river network structure of SPNA shifted from a complex reticular structure to a simpler, non-reticular one. The current structure is negatively related to urbanization level. A reticular network, which composed of only main rivers, was present in the central area.

iv. Rapid urbanization reduced river channel storage capacity, and the quantity of drainage pumping stations continuously increased to compensate for the capacity.
This produced significant negative correlation with indicators of river network structure. To protect the natural river network, it is suggested that the protection and maintenance of some lower-order rivers would make better connectivity of the network.

v. It was revealed that the CRIS, especially the new indicators $R_z$ and $\beta$ proposed in this study, can well reflect the structure change in reticular river network under rapid urbanization, and different indicators in CRIS have showed differentiated sensitivity to urbanization, confirming that the selection of the framework of indicators is powerful. Although the urbanization speed of the study area was much higher than that of common regions, the urban expansion rule of SPNA may not be different from that of other cities in the world.

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**Abbreviations**

| Name                               | Abbreviation |
|------------------------------------|--------------|
| Shanghai’s Pudong New Area         | SPNA         |
| Comprehensive River-network Indicator System | CRIS         |
| Lujiazui Financial and Trading Zone | LJZ          |
| Jinqiao Export Processing Zone     | JQ           |
| Zhangjiang High-Tech Park          | ZJ           |
| Waigaoqiao Free Trade Zone         | WGQ          |
| Chuansha Zone                      | CS           |
| Sanlin World Expo Zone             | SL           |
| Water area percentage              | $W_P$        |
| River density                      | $R_d$        |
| River frequency                    | $R_f$        |
| River development                  | $R_z$        |
| Average branch ratio               | $R_b$        |
| Connectivity ratio                 | $\beta$      |

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