Impacts of urbanization on hydrology in the Yangtze River Delta, China
Xu Youpeng, Xu Jintao, Ding Jinjia, Chen Ying, Yin Yixing and Zhang Xingqi

ABSTRACT

The Yangtze River Delta is one of the most developed regions in China and the rapid development of urbanization have greatly influenced regional hydrology and water resources. Taking several typical urbanizing areas in the Yangtze River Delta as examples, this paper probes into the impacts of urbanization on hydrologic cycle and hydrological process with the support of RS, GIS and hydrological model. The research centers on the impacts of urbanization on precipitation, hydrological process, river networks, and water environment in some typical cities. The results show that: (1) Urban rain island effect is not evident when the process of urbanization is slow, while the differences of annual precipitation and flood season precipitation between urban and suburban areas increased to a certain extent in the booming stage of urbanization. (2) The annual runoff depth and the runoff coefficient increased with the development of urbanization, and the effect will be more notable when the urban areas expand to a certain size; (3) River network systems, especially low-grade rivers have been greatly destroyed in the process of urbanization, which increases the risk of flood and water degradation, so it is very important to protect natural river systems. Based on the results, some proposals of sustainable utilization and protection of water resources is also addressed.

Key words | hydrological response, the Yangtze River Delta, urbanization

INTRODUCTION

For the past few years, the rapid urbanization of watersheds in China, involving increment of impervious areas, and decrement of natural drainage networks, has significant impacts on regional hydrology, water resources and stream quality. The problems of flood and drought intensification, water quality deterioration and the shortage of water resources in cities, seriously threaten the living environment of human beings and restrict the sustainable development of regional economy. Therefore, the study of hydrological response (including river network systems, hydrological cycle, hydrographs, etc) to urbanization has become the focus of attention on hydrology research (Yin & Li 2001; Chen et al. 2002; Chen et al. 2009a).

Urban hydrology has received wide concerns since 1970s in the world. Some prominent observation and study has carried out in Europe, the United States and other developed countries. Study of urban effects on hydrology was developed in the “International Hydrological Decade” plan of Unesco in 1975. Later, some scholars compiled monographs of urban hydrology, and studied several aspects of urban hydrology. The effects of urbanization on hydrology have been documented in the literature from different perspectives, including the study of the spatial variability of urbanization and its effect on runoff generation (Konrad & Booth 2002; Greer & Stow 2003), the analysis of runoff changes in response to land use changes (Beighley & Moglen 2005; Bari et al. 2005), and the prediction of runoff for future climatic and land use conditions (Dewalle et al. 2000) etc.

With the acceleration of urbanization in 1980s in China, much research on urban hydrology has been
developed gradually, and there has been much work carried out in the Yangtze River basin (Yuan et al. 2006; Zhang et al. 2006). By the study of the human impact on floods and flood disasters in the Yangtze River basin, Yin & Li (2001) believe that the deteriorating flood situation is the result of inappropriate human intervention in the natural environment and suggest that the appropriate strategy should change from “keeping the flood away” to “giving the flood way”. By using Horton-Strahler classification and Horton laws, a novel method of classification in conjunction with the traditional and specially designed indicators, was applied to understand the structure and functions of the river system in Shanghai (Yuan et al. 2006). According to Zhang et al. (2008), human activities such as dredging up the floodways, excavating sand and building water facilities in the rivers, significantly changed the hydrological conditions, and therefore impaired the rivers’ capacity to buffer floods over the past decades. What’s more, the temporal and spatial trends of precipitation and river flow over the Yangtze River basin were analyzed, and it was speculated that the increase in heavy precipitation and variations of atmospheric circulation (weakened summer monsoon) under climate warming in the middle-lower reaches can partly explain the frequent occurrence of floods in the 1990s (Jiang et al. 2007; Su et al. 2008).

The Yangtze River Delta (YRD) is one of the most economically developed regions in China. With rapid urbanization and industrialization in recent years, and the expansion of the urban areas and impervious areas, lake wetlands and river network systems have been greatly destroyed, which has inevitably changed the regional hydrology. Furthermore, the problem of flood disasters and water degradation has been serious increasingly. So it is really necessary to study the urban hydraulic effects here.

There is not yet an unified cognition about urban hydraulic effects so far, because hydrological changes are affected by various factors in urban areas and have regional characteristics. In fact, there is a close relation between frequent occurrence of flood disasters, water environment deterioration and meteorological factors, underlying conditions, geographical conditions as well as human activities in the YRD. Climatic change, urbanization, and landuse/land cover change have all greatly changed the hydrologic cycle in this area. Climatic change has intensified the hydrologic cycle process and increased the risk of flood disasters. And the changes of drainage networks resulted from urbanization also have a significant impact on the flood processes. Moreover, the decline of drainage networks and river channel sedimentation have decreased the purification capacity of the rivers. Besides, the characteristics of urban hydrology is also influenced by the different periods of urbanization. In a word, under the influences of a variety of comprehensive factors, flood disasters occur frequently and water environment problems become more and more serious, which have restricted the modernization and the sustainable development of the YRD to a very great extent. It is very important to investigate integratively the impacts of urbanization on hydrology in this area for the utilization of water resources and sustainable development. There have been some scattered research on megalopolises in the YRD, like Shanghai and Nanjing (Zhou et al. 2003; Yuan et al. 2006). However, those fast urbanizing big and medium-sized cities, like Suzhou, wuxi and Changzhou, etc, are less studied. So it is urgent to explore the urban hydrology characteristics from the aspect of urban agglomeration, especially to investigate integratively the impacts of urbanization on precipitation, runoff, river networks and water quality.

Taking several typical urbanizing areas in the YRD as examples, using the long-term rainfall-runoff data, this paper evaluates the hydrological response of urbanization to hydrologic cycle and hydrological process with the support of RS and GIS. The research centers on the impacts of urbanization on precipitation, hydrological process, river networks, and water environment in some typical cities. Moreover, the characteristic statistic analysis, time series analysis methods and hydrological simulation are adopted in the study (Aronica & Cannarozzo 2000). The results can provide basis for decision-making in flood prevention and disaster reduction, water environmental protection and sustainable utilization of water resources, it also provides support to regional economic development.

**STUDY AREA**

The YRD is one of the most typical plain river network regions in China, including 15 prefecture-level cities of Jiangsu Province, Zhejiang Province and Shanghai...
(Figure 1). The area is about 99,000 km², and the population is about 75 million. The YRD, with dotted crisscrossed rivers and dense water system, is a part of the Middle-lower Yangtze Plain. The main rivers include Huangpu River, Dongtiaoxi, Xitiaoxi, Cao’e River, Yong River, Qinhai River, and the other Circum-Taihu Lake rivers, etc. The YRD is now one of the biggest urban agglomerations in the world. Although it only covers 1% of Chinese territory and 6% of Chinese population, it brings about 17% of the GDP in China, so it is the most developed regions in China (Dong 2004).

However, with the rapid development of economy and continuous expansion of industrialization and urbanization, lakes and river systems are destroyed which has greatly changed the hydrologic characteristics of the study area. As a result, flood/drought disasters and water environment deterioration are becoming increasingly serious problems (Xu et al. 2003). Human’s living environment has changed and consequently sustainable development of economy is restricted.

**MATERIALS AND METHODS**

Shanghai, Nanjing and Hangzhou are the three mega cities in the YRD, while their urbanization process is not the most significant in the study area recently due to their relatively early urbanization. By contrast, Suzhou, Wuxi and Changzhou urban agglomeration (Suxichang for short) is the typical area with rapid urbanization in recent years. The urbanization process of Suxichang has mainly undergone three periods: relatively slow period from 1961 to 1978, fast period from 1979 to 2000, and stable period from 2001 to 2006. Thus this study chooses Suzhou, Wuxi and Changzhou to investigate the influences of urbanization on rainfall characteristics such as annual rainfall, flood season rainfall and annual maximum daily storm based on the three urbanization periods. The precipitation data are available for urban and suburban contrastive analysis. The typical urban and suburban stations are chosen, and their distances are within 20 to 25 km. Besides, the suburban stations are less influenced by urbanization. What’s more, the meteorological conditions are very similar due to the low relief degree in the plain river network region. Based on the rainfall time series from 1961 to 2006, we perform the analysis by comparing representative suburban precipitation with representative urban precipitation in the same period, and comparing the rainfall at each station in the three urbanization periods.

The rivers are dotted crisscrossed and there is not a certain outlet in the manually controled plain river network area. So when we study the impacts of urbanization on long term runoff, the relatively closed basins of Xitiaoxi in Anji County and Nantiaoxi in Lin’an County are chosen to do
the analysis by using L-THIA (Long-Term Hydrological Impact Analysis) model (Christopher 2001). The chosen basins are both located in Taihu upstream, in the growth stage of urbanization and the selected gauge stations are Hengtangcun and Lin’an (Figure 1). The adopted data include long-term hydrological data from 1964 to 2006 and two sets of landuse data (1985 and 2000). Moreover, one urban district has been set up for hydrological experiments. The rainfall-runoff process of this urban district is being observed, in order to analyze the influences of landuse change on storm-runoff in different periods of urbanization.

L-THIA model is developed on the basis of SCS model designed by U.S. Department of Agriculture Soil and Water Conservation Bureau. Supported by GIS, L-THIA model takes many factors into consideration, including underlying surfaces and hydrological soil characteristics. CN is the most important parameter to calculate the rainfall-runoff of different HRUs in watersheds. Land covers are classified by GIS first, and then underlying surfaces are rasterized by spatial analysis. CN values are determined by spatial overlay analysis at last. Runoff is calculated according to rainfall and other input data. By using L-THIA model, the impacts of landuse change and increment of impervious areas in the urbanization process on the runoff are quantitatively analyzed. On this basis, the influences of urban expansion on runoff are simulated and predicted (Li et al. 2006).

For the research of urbanization impacts on drainage networks and water environment, the Fenghua River watershed in the southeast of the YRD (near the city of Ningbo) is taken as an example due to the available data of stream structure here. The database includes airborne remote sensing data of 1990 and 2003, landuse status of 1990 and 2003, and monitoring data of water quality from 1992 to 2004. Additionally, overlaying analysis, measurement of river gradation and other statistical analysis methods are adopted in the analysis.

RESULTS AND DISCUSSION

Impacts on precipitation

Suzhou, Wuxi and Changzhou, the three typical urbanized areas in the YRD, have constituted one of the biggest urban agglomerations in the world, called the Suxichang urban area. Rapid urbanization has greatly changed the environment and the climate such as the rainfall process. The representative urban precipitation and the representative suburban precipitation in the same period in the three cities

### Table 1 | Annual precipitation in Suxichang area

<table>
<thead>
<tr>
<th>Year</th>
<th>Suzhou¹</th>
<th>Wangting²</th>
<th>Wuxi¹</th>
<th>Qingyang²</th>
<th>Changzhou¹</th>
<th>Jintan²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1961–1978</td>
<td>1,036.6</td>
<td>951.0</td>
<td>1,064.9</td>
<td>990.1</td>
<td>1,108.2</td>
<td>1,057.9</td>
</tr>
<tr>
<td>1979–2000</td>
<td>1,154.2</td>
<td>1,103.2</td>
<td>1,138.8</td>
<td>1,066.7</td>
<td>1,110.4</td>
<td>1,086.3</td>
</tr>
<tr>
<td>2001–2006</td>
<td>1,107.0</td>
<td>1,000.3</td>
<td>1,103.4</td>
<td>999.1</td>
<td>991.4</td>
<td>1,032.6</td>
</tr>
</tbody>
</table>

¹ refers to the station of urban precipitation.
² refers to the station of suburban precipitation.

### Table 2 | Flood season precipitation in Suxichang area

<table>
<thead>
<tr>
<th>Year</th>
<th>Suzhou¹</th>
<th>Wangting²</th>
<th>Wuxi¹</th>
<th>Qingyang²</th>
<th>Changzhou¹</th>
<th>Jintan²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1961–1978</td>
<td>498.9</td>
<td>452.9</td>
<td>520.7</td>
<td>513.1</td>
<td>569.4</td>
<td>550.9</td>
</tr>
<tr>
<td>1979–2000</td>
<td>618.9</td>
<td>573.4</td>
<td>624.1</td>
<td>566.8</td>
<td>587.7</td>
<td>561.3</td>
</tr>
<tr>
<td>2001–2006</td>
<td>507.3</td>
<td>475.1</td>
<td>560.1</td>
<td>511.4</td>
<td>481.6</td>
<td>478.0</td>
</tr>
</tbody>
</table>

¹ refers to the station of urban precipitation.
² refers to the station of suburban precipitation.
are analyzed (Tables 1 and 2). Suzhou, Wuxi and Changzhou are compared with Wangting, Qingyang and Jintan, respectively.

Tables 1 and 2 shows that, under the identical meteorological conditions, the increment of precipitation in the urban areas of Suzhou and Wuxi is more than that in the suburban areas as a result of urbanization. Because of the influence of atmospheric circulation, the precipitation in the study area has decreased gradually, but there are still differences between the urban and the suburban areas from 2001 to 2006 for the reason of urbanization. Moreover, results of the rescaled range (R/S) analysis of the precipitation time series indicate that urbanization will intensify the influence on the precipitation in the near future with the development of urbanization (Figure 2).

Tables 1, 2 and Figure 2 also indicate that, urbanization has greatly influenced the precipitation in Suxichang area, but the results vary between the annual precipitation and flood season precipitation. What’s more, the increment of precipitation in Suzhou and Wuxi is more obvious than that in Changzhou, whose urbanization process is relatively slow than the former two areas.

The differences of the annual precipitation in the urban and the suburban areas of Suzhou and Wuxi, are 21.1 mm from 1961 to 1978 and 29.5 mm from 2001 to 2006 respectively, while the differences of the flood season precipitation are −7 mm and 41 mm. The reason for urban rainfall island effect is that the urban microclimate is changed with the increment of high buildings and impervious area, and more condensation nuclei are formed in the air which is benifitial for rainfall formation. Moreover, meteorological factors such as precipitation can affect the precipitation differences between the urban and the suburban areas besides the factor of urban underlying. Results show that, the less the annual precipitation is, the bigger the difference is. But contrarily, the more the flood season precipitation is, the bigger the difference is. The difference between urban and suburban precipitation in Changzhou is relatively small, probably because of the relatively slow urbanization. The difference between the urban and the suburb areas will possibly be bigger in the near future with the development of urbanization. With the background of the current large scale circulation system, urban development will intensify its influences on the precipitation in Suxichang area. But results may vary in each city, and individual city such as Changzhou may be even an exception.

Furthermore, statistics of the maximum daily rainfall and the frequency of different types of rainfall show that, the maximum daily rainfall and the frequency of different types...
of rainfall have all increased due to urbanization, among which the increment of rainstorm is especially the most significant. The results are consistent with the research findings made in Nanjing, Shanghai and Hangzhou, which are also in the YRD (Zhou 2003; Qin et al. 2005). And the increased range in Suxichang area is much bigger than that in the 3 bigger cities. However, uncertainty exists in the impact of urbanization on precipitation, and Changzhou is an example.

Impacts on runoff

Impacts on long-term runoff

The two small basins, centered in the Lin’an and Anji County, are fast urbanized areas characterized by great increase in built up land. This study modeled the long term impacts of urbanization on runoff according to the land use data of before and after urbanization. Based on the rainfall-runoff data from 1964 to 1977, from 1978 to 1998 and two sets of landuse data in the Nantiaoxi watershed, the annual runoff is calculated by L-THIA model. The errors are only 3% and 2.6% respectively, thus the simulation result is satisfied, and the L-THIA model can be used for simulation and prediction in the study area. Comparative analysis results show that the annual runoff depth increases from 669.5 mm to 861.8 mm from the period of 1964–1977 to 1978–1998, and the runoff coefficient increases from 0.51 to 0.60; while the ratio of urbanized area in total basin area increases from 4% in the late 1990s to 20% (about 36.6 km²). The adopted daily rainfall is the time series of 1978–1998 in the process of modeling. By future scenario analysis, it can be concluded that the impacts of urbanization on runoff become obvious when the urban land develops to a certain scale with the identical rainfall series. The annual runoff depth and the runoff coefficient also tend to increase in the forthcoming years.

As for the Xitiaoxi watershed, the rainfall-runoff data from 1972 to 1985, and the landuse data of 1985 is used for calibration and verification of L-THIA model. The error of the average annual runoff is 6.6%, so the model can be used for further analysis. On this basis, the rainfall data from 1986 to 2003 and the landuse data of 2000 are used for simulation, and then the runoff of the two periods is compared. The results indicate that the runoff depth increases from 813.4 mm to 826.4 mm from the period of 1975–1985 to 1986–2003, and the runoff coefficient has increased by 4%; while the ratio of urbanized area in total basin area increases from 3.2% in the mid 1980s to 10.6% at the present. However, the rainfall of the period 1986 to 2003 is less than that of 1972 to 1985 by 29.3. These suggest that the infiltration decreases and surface runoff increases with the urban expansion and growth of impervious surface area, resulting in the increment of runoff coefficient. In addition, with the identical rainfall series, the impacts of urbanization on runoff in the future are predicted. Results show that the annual runoff depth and the runoff coefficient will increase with the development of urbanization.

In order to investigate whether the landuse change has consistent impacts on runoff generation in dry, normal and wet years, a frequency statistics is made on the area precipitation from 1972 to 2005, and the theoretical frequency curve of the annaul precipitation is obtained. Based on this, the years 1983, 1998 and 1972 are chosen as the wet, normal and dry years, whose annaul rain frequencies are 10%, 50%, 90%, respectively. The three typical years are then correspondingly used to measure the runoff depth in landuse scenarios of 1985, 2002 and 2017 (Table 3).

Results show that, different annual precipitation have big differences in influencing the runoff under the condition of similar developed level of urbanization. The influence in the dry year is the most significant while the influence in the wet year is the weakest. The reason is that precipitation characteristics also restrict the runoff in addition to the landuse change. There is less precipitation in dry years, so influence of land use change on runoff is more significant. However, there is more precipitation in wet years, so the influence of underlying surface change is weakened, which results in relatively small runoff change.

To sum up, the urban expansion has greatly influenced the runoff in the study region. Landuse types and soil types are the main driving factors, while intensity and spatial variability of precipitation should also be paid attention to. As to a certain region, the runoff of urban area is more than that of the suburban area. Generally, with the expansion of urban land area, the surface runoff increases correspondingly. And the influence of urbanization on runoff is
a long-term process. So the expansion of urban land should not be unrestricted in the urbanization process.

**Impacts on storm-runoff**

According to the analysis of urbanization impacts on storm runoff in the Nantiaoxi watershed, when the ratio of urbanized area in total watershed area increases from 0.5% in 1970s to 3.3% in 1990s, the runoff depth increases 4.8 mm in a rainstorm of 50.8 mm. Moreover, with the increment of rainfall, the runoff depth increases more remarkably. In the condition of the same antecedent moisture condition (AMC) and rainfall pattern both the runoff depth and the runoff coefficient will increase with the development of urbanization and increment of imperviable areas. As for the Xitiaoxi watershed, when the ratio of urbanized area in total watershed area increases from 8.4% in 2002 to 20% in 2017, the runoff depth increases 7.1 mm in a average rainstorm of 180 mm, and the peak discharge will be increased by 51.2 m³/s. It can be concluded that the increment of urban land area can directly influence the characteristics of floods.

**Experimental study of urbanization influences on storm-runoff**

Small catchments with different types of landuse/land cover (built up land, forest land, grass land and farmland) were chosen in the Xitiaoxi watershed for the analysis of hydrological response to different levels of urbanization. The contrastive rainfall-runoff observation is carried out in this area. The entire area of the experimental district is about 35 km². The synchronous observation and experimental analysis is carried out on rainfall-runoff and storm-runoff. In addition, water quality sampling is done in the subdistricts during storm flood periods for the experimental observation and research of water quality change with the landuse/land cover changing. Now the observations are in the works, and the preliminary observed results have proved the rules of hydrologic processes such as increment of flood peak and shortening of flood lasting time in urban areas.

**Impacts on river network systems and water environment**

The YRD is one of the most typical plain river network regions in China with dotted crisscrossed rivers and dense water system. With the development of urbanization, urban imperviable areas have increased dramatically, while many lakes and rivers have decreased sharply. In the 1990s, more than 20 relatively large rivers disappeared and the drainage density decreased by 25% in Nanjing urban district (Wang 2006). The river channels and the water surface ratio decreased by 21% and 23% in Shanghai in the last 5 years of 1990s respectively. The drainage network structure tends to be more simple and the drainage density decreases, resulting in frequent flood disasters and water pollution accidents in Shanghai (Ren et al. 2003; Meng et al. 2005).

The river system of Fenghua River basin in the southeast of the YRD are analyzed before and after urbanization (Table 4). It can be seen that, the development of urbanization greatly changed the drainage network and made the rivers much narrower and shorter. The number of non-main rivers is decreasing gradually. Many small streams disappeared from 1990 to 2003, and the total length of the rivers was shortened by 18.15 km. The drainage density and water surface ratio have decreased by 2.4% and 13.8%, respectively. The water surface ratio of

### Table 3 | Annual runoff depth of different rainfall frequency in 1985, 2002 and 2017 (Chen et al. 2009b)

<table>
<thead>
<tr>
<th>Rainfall frequency</th>
<th>Annual rainfall of typical Years/cm</th>
<th>R’/mm</th>
<th>1985</th>
<th>2002</th>
<th>2017</th>
<th>A/cm</th>
<th>B/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>10%</td>
<td>186.93</td>
<td>127.8</td>
<td>132.13</td>
<td>135.72</td>
<td>4.33</td>
<td>3.39</td>
<td>7.92</td>
</tr>
<tr>
<td>50%</td>
<td>151.29</td>
<td>63.39</td>
<td>67.07</td>
<td>70.04</td>
<td>3.68</td>
<td>5.81</td>
<td>6.65</td>
</tr>
<tr>
<td>90%</td>
<td>104.81</td>
<td>38.94</td>
<td>41.32</td>
<td>43.25</td>
<td>2.39</td>
<td>6.13</td>
<td>4.31</td>
</tr>
</tbody>
</table>

R refers to annual runoff depth.
†A refers to the absolute amount of runoff depth change.
‡B refers to the relative amount of runoff depth change.
the non-main rivers is decreasing at the rate of 1% per year (Table 4). The drainage network structure is directly related to the process of urbanization and the relationship will be more remarkable with the development of urbanization. As a result of rapid urbanization, the capacity of flood storage has weakened greatly. The urban drainage system is far from perfect, which increases the probability of storm waterlogging. The threat of flood is increasing as a result of urbanization. For example, the maximum flood level is increasing at the rate of 5.4 cm per year in this period. Besides, the channel scouring and the water purification capacity have been weakened which leads to deterioration of water environment. For instance, the water quality was the third grade in 1992, while 85% of the river water belonged to the fifth grade in 2004. The urban expansion and the deterioration of water environment shows considerable consistency, which indicates that urbanization has great impacts on the aquatic ecosystem and water environment.

**CONCLUSIONS**

According to the above analysis, the rapid urbanization in the YRD has greatly influenced the regional laws of hydrology by changing impervious areas and river network systems. Firstly, with the rapid development of urbanization, the annual precipitation and the flood season precipitation in the urban areas showed a striking increase, and the disparity between the urban and suburban areas is getting widened. Urban rain island effect is being enhanced year by year, but there is also regional uncertainty and complexity which needs more further research to clarify. Secondly, both long-term runoff and storm-runoff are affected by urbanization. Especially when the urban areas expand to a certain size, the runoff depth and the runoff coefficient will increase more remarkably. The results also show that, the influence of urbanization in the dry year is the most significant among dry, normal and wet years. Thirdly, river network systems, especially low-grade rivers have been greatly destroyed. As a result, the river channels and the water surface ratio decreased obviously, and the water purification capacity and the regulation and storage capacity of the rivers have decreased remarkably, which increases the risk of flood and water degradation.

Based on the results of the current study, some suggestions on the management of regional water resources are proposed as follows. First, natural and artificial factors should be synthetically considered for an appropriate development of urbanization. Second, the natural evolution laws of rivers should be followed and the original rivers should be retained in order to maintain the appropriate water surface ratio, to strengthen the storage capacity of the river network systems, and to diminish the threat of floods. Further more, pollution control should be reinforced and the water quality of the lakes and rivers should be improved.
to protect the aquatic ecosystem and water environment. Only in this way can we make the sustainable economic development in the YRD and realize the sustainable utilization of the water resources in this area.

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