Effects of river sinuosity on the self-purification capacity of the Shiwuli River, China
Chenguang Xiao, Jing Chen, Dan Chen and Ruidong Chen

ABSTRACT
This study focused on the correlation between river sinuosity and self-purification capacity, using the Shiwuli River in Hefei, China, as a case. Through field monitoring, the reduction rate of each pollutant per unit length of river reach and its correlation with the corresponding sinuosity were analysed. The results show that river sinuosity has different degrees of positive correlation with the growth rate of dissolved oxygen (DO) and the reduction rates of total nitrogen (TN), ammonia nitrogen (NH3-N) and total phosphorus (TP). River sinuosity needs to be above 1.42 to ensure the river’s basic self-purification capability. We also discuss the mechanism of river sinuosity on water body self-purification and propose the increase in river sinuosity to improve the river’s capacity to purify water from pollutants. This measure could enhance the growth rate of DO, the longitudinal hyporheic exchange flow, and the action time of other basic self-purification factors of the river. This study could help scientific decision-making in river reconstruction planning in the process of urbanization in the middle and lower reaches of the Yangtze River in China.

Key words: meandering stream, river sinuosity, self-purification capacity, Shiwuli River, water quality

INTRODUCTION
The self-purification capacity of rivers is an important property to maintain river water quality and ensure the ecological stability of rivers. Its influence factors include the flow state of the river, the distribution of aquatic plants on the bank slopes, sunshine duration, climatic conditions, sediment composition, the species and quantity of aquatic animals and microorganisms in the water (Sabater et al. 2002; Vagnetti et al. 2003). Yet river morphology is a key factor among them. In recent years, in China’s rapid urbanization process, the improvement of land use efficiency and flood safety has been one-sidedly emphasized regardless of river protection in some areas. Some rivers have suffered from some ‘destructive’ construction projects; for example, levelling river channels, straightening river bends and rigidifying river channels. These projects have dramatically altered the natural shape of rivers and led to environmental issues including water quality deterioration and biodiversity loss (Che et al. 2012).

River sinuosity is one of the most important indicators of river morphology (Mueller 1968). Variations in river sinuosity lead to changes in water flow characteristics (Han & Endreny 2013). With an increase in the degree of river meandering, water can flow over to the beaches of the river to form a longitudinal hyporheic exchange flow, increasing the volume of exchange between underground water and ground water (Peterson & Sickbert 2006; Cardenas 2008, 2009). River sinuosity has a considerable impact on the ecological environment. For example, the biomass and number of fauna in meandering river reaches are higher than those of manually straightened river reaches (Lorenz et al. 2009). Restoration of straightened river bends significantly improves the biological habitats.
and ecosystems along the river (Moerke & Lamberti 2003). It was also shown that the flow of meandering rivers had an impact on water quality. Dwivedi et al. (2017) found that hyporheic flow in meandering rivers played an important role in the migration of nitrogen in river systems. A preliminary study on the relationship between river sinuosity and water quality indicated that in the sinuosity range of 1–1.07, river reaches with a high degree of river meandering showed a higher capacity for water body self-purification (He 2014).

The review of past studies indicates that river sinuosity-related investigations have mainly been concentrated on the morphology and ecology of rivers. However, relatively few studies focused on the impacts of variations in river sinuosity on water quality. The quantitative relationship and mechanism between a river’s sinuosity and its self-purification capacity have not been adequately addressed. In this study, through field monitoring of the water quality in different reaches of the Shiwuli River, the correlation between river sinuosity and the self-purification capability was established and analyzed. The effect of river sinuosity on the reduction of pollutant concentrations is also discussed in the last section.

**METHODOLOGY**

**Study area**

Chaohu Lake is one of China’s five largest freshwater lakes. In recent years, the water pollution problem in Chaohu Lake has become more and more serious. Shiwuli River is the most polluted river in the Chaohu Lake Basin and the most important source of water pollution in Chaohu Lake. The middle and upper sections of the Shiwuli River are located in the main urban area of Hefei City, China. A large number of river sections have been artificially modified: some narrowed and renovated with cement structures, some straightened, and some buried to become an underground stream. The lower section of the Shiwuli River (Figure 1) is located in the middle of the Old Downtown and the New Lakeside District of Hefei City, an area to be urbanized, encircling the new site of the compound of the Anhui Provincial Government. As the New Lakeside District develops from Chaohu Lake towards the north and the Old Downtown expands towards the south, coupled with the aggregation effect brought by the relocation of the provincial government compound, this river section is...
facing the risk of being straightened in the urbanization renovation.

In this study, the lower section of the Shiwuli River (31°45'35.12″N, 117°19'54.93″E to 31°43'18.89″N, 117°21'41.59″E) was used as the subject. It is 7.8 km long, with a certain degree of sinuosity, and is currently free of point and non-point source pollution. The average width and average gradient of the river section are 25 m and 0.72 ‰, respectively, and the water depth and annual runoff are approximately 2.5–3.5 m and 2,000 m³, respectively. The water quality of this river section is perennially below grade V (the worst level in China’s water quality classification). The cross section of the river channel is U-shaped, and the river width, water depth, and cross-sectional shape rarely change along the river. Therefore, the study river section is regarded as one with the same condition on other factors without any interference except for sinuosity, and only the effects of two major factors (sinuosity and water quality) and the underlying mechanisms are investigated in this study.

Field experiment

River sinuosity S refers to the ratio of the actual length (along the river) to the linear distance (straight line) between the upstream and downstream of a river section, and S is calculated using the following formula:

\[ S = \frac{L_T}{L_0} \]  

(1)

where \( L_T \) is the actual length of the river section measured along the river’s central axis; \( L_0 \) is the linear distance between the upstream and downstream of the river section. In this study, 17 water quality monitoring sites were set up along the study river section, of which Site 17 was at the upstream limit and Site 1 was at the estuary to Chaohu Lake as the downstream limit (Figure 1). Nine sites (Sites 1, 2, 4, 7, 8, 10, 13, 15, and 17) covered eight meandering reaches (1–2, 2–4, 4–7, 7–8, 8–10, 10–13, 13–15, and 15–17), with a sinuosity level ranging from 1.00 to 1.84 (1.00, 1.14, 1.84, 1.02, 1.65, 1.30, 1.22, and 1.56, respectively). Each river reach only has a single bend, with similar conditions of surrounding environment, bank structure, climate, and water source; except for the different levels of sinuosity, the other river indicators are essentially identical.

Water quality samples were taken three times on the study river section, respectively in autumn (in November 2017; temperature: 23 °C), winter (in February 2018; temperature: 0 °C) and spring (in May 2018; temperature: 24 °C). In each experiment, three parallel samples were taken from each sampling point. The water samples were analysed in the Anhui Water Environment Monitoring Laboratory. The water quality analysis on five key indicators, dissolved oxygen (DO), total nitrogen (TN), ammonia nitrogen (NH3-N), total phosphorus (TP) and chemical oxygen demand (CODCr) is strictly conducted in accordance with China’s national standards. The main monitoring methods include iodometric method, spectrophotometry method and dichromate method. The main analytical instruments include ultraviolet and visible spectrophotometer, microwave digestion system, pressure steam sterilizer, etc.

RESULTS

The monitoring results of three field experiments are shown in Figure 2.

The water quality results of the three inspections were very poor in the whole section of the studied river, and the concentration of each pollutant in winter was slightly higher than that in autumn. Meanwhile, according to the analysis of raw data (the trend is shown in Figure 2), the Shiwuli River showed a certain purification effect on nitrogen and phosphorus in the water from the upper reach, which was more pronounced in autumn and spring when the temperature was relatively high.

Based on the above data, the reduction rate (R) of each pollutant along the river section (Formula (2)) was calculated to obtain the purification efficiency of each pollutant per unit length of each reach with different sinuosity:

\[ R = \frac{C_0 - C_1}{C_0 L_T} \]  

(2)

where R is the reduction rate of the pollutant along the river section (km), and \( C_0 \) and \( C_1 \) are the corresponding concentrations of a given water quality indicator at the upper reach.
and the lower reach limits (mg/L), respectively; \( L_T \) is the length of the river section along the central axis of the river (km).

Among the monitored indicators, DO is a positive indicator of water body self-purification. In the remainder of this paper, DO is expressed as a growth rate along the river section, as calculated by Formula (2), from which the negative value is taken (denoted as \(-R\) (DO)). The results of \( R \) in different seasons are shown in Tables 1–3.

The inspection data were analysed using linear regression analysis, the results of which are shown in Figure 3.

The results show that within the range of river sinuosity examined in this study (1–1.84), river sinuosity had a significantly positive correlation with the growth rate of DO (\( P < 0.01 \) in autumn and spring), which increased continuously with increasing river sinuosity. Based on the growth trend line, the growth rate of DO changed from negative to positive in the autumn when the sinuosity was 1.37 and did so in the winter when the sinuosity was 1.40 and in the spring when the sinuosity was 1.29. The trends in the

Table 1 | Self-purification capacity of water quality indicators in various river reaches in autumn

<table>
<thead>
<tr>
<th>Meandering reach</th>
<th>( s )</th>
<th>(-R) (DO)/km</th>
<th>( R) (TN)/km</th>
<th>( R) (NH\textsubscript{3}-N)/km</th>
<th>( R) (TP)/km</th>
<th>( R) (COD\textsubscript{Cr})/km</th>
</tr>
</thead>
<tbody>
<tr>
<td>15–17</td>
<td>1.36</td>
<td>0.41</td>
<td>0.10</td>
<td>0.06</td>
<td>0.07</td>
<td>0.22</td>
</tr>
<tr>
<td>15–17</td>
<td>1.22</td>
<td>0.08</td>
<td>0.17</td>
<td>0.03</td>
<td>0.00</td>
<td>−0.02</td>
</tr>
<tr>
<td>10–13</td>
<td>1.30</td>
<td>−0.17</td>
<td>−0.12</td>
<td>−0.01</td>
<td>0.02</td>
<td>−0.08</td>
</tr>
<tr>
<td>8–10</td>
<td>1.65</td>
<td>0.53</td>
<td>−0.20</td>
<td>0.07</td>
<td>0.12</td>
<td>0.14</td>
</tr>
<tr>
<td>6–7</td>
<td>1.02</td>
<td>−0.52</td>
<td>0.40</td>
<td>0.00</td>
<td>−0.27</td>
<td>0.05</td>
</tr>
<tr>
<td>4–7</td>
<td>1.84</td>
<td>0.39</td>
<td>−0.10</td>
<td>0.08</td>
<td>0.17</td>
<td>0.14</td>
</tr>
<tr>
<td>2–4</td>
<td>1.14</td>
<td>−0.35</td>
<td>0.08</td>
<td>−0.05</td>
<td>−0.23</td>
<td>−0.11</td>
</tr>
<tr>
<td>1–2</td>
<td>1.00</td>
<td>−0.02</td>
<td>−0.50</td>
<td>0.02</td>
<td>−0.20</td>
<td>−0.42</td>
</tr>
</tbody>
</table>

Figure 2 | Water quality measurements of the Shiwuli River. (a) Water quality results of the autumn measurement. (b) Water quality results of the winter measurement. (c) Water quality results of the spring measurement.
rates of reduction of TN and NH₃-N were consistent with the DO growth rate, rising with increasing river sinuosity (P < 0.05 in autumn and PₓTN < 0.01 in winter). At low temperature, the reduction rate of TN was significantly lower than that at high temperature, which changed from negative to positive when the sinuosity was 1.42 according to the trend line. In the autumn, NH₃-N exhibited a higher positive correlation with river sinuosity (P < 0.05) and changed from negative to positive when the sinuosity was 1.36 and did so in the spring when the sinuosity was 1.23. At high temperature, the reduction rate of TP showed a rising trend similar to that of the growth rate of DO and changed from negative to positive when the sinuosity was 1.42 in the autumn and 1 in the spring, but showed no significant correlation with river sinuosity at low temperature. The correlation between river sinuosity and the reduction rate of CODₜ was not significant and no uniform pattern was shown in the three experiments.

### DISCUSSION

Based on the above field monitoring results, we found that at higher temperature, river sinuosity has an increased effect on river self-purification capacity. Among the five water quality indicators monitored, the increase in river sinuosity has the most significant effect on the growth rate of DO. The increase in river sinuosity enhances the impact of the flowing water on river banks, generates eddy and turbulent flows at varying degrees, and increases the aeration of the water, resulting in the increase in DO. River sinuosity also has a significant effect on the reduction rates of TN and NH₃-N, and the possible underlying mechanisms are as follows. (1) The increased DO derived from the increased river sinuosity accelerates the oxidative decomposition of nitrogen compounds. (2) Simultaneously, the shape of the river becomes more meandering as the level of sinuosity increases, which intensifies longitudinal hyporheic exchange flow and enables the water to transport organic carbon-rich sediments in a low-oxygen environment for a longer duration. This relatively longer residence time increases the rate of denitrification of nitrate nitrogen, ultimately leading to the conversion of nitrogen in water into emitting nitrogen gas (Peterson et al. 2001; Dwivedi et al. 2017). (3) The continuous meandering of the river allows for a greater volume of water to stay in the alternating oxygen-rich and anaerobic environments, further strengthening the purification of nitrogen. At high temperature, the effect of river sinuosity on the reduction rate of TP is significant, and the possible underlying mechanisms are as follows. (1) The increased DO resulting from the increased level of river sinuosity accelerates the conversion of organic phosphorus to occluded phosphates (Pan et al. 2016). (2) Simultaneously, the increase in sinuosity either blocks the water flow or decreases the flow velocity, which facilitates the precipitation of the phosphates. (3) Moreover, the longitudinal hyporheic exchange flow caused by river meandering enhances phosphorus fixation by the soil of river banks. In winter, the low temperature likely causes the significant reduction in the removal efficiency of phosphorus from

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Table 2 | Self-purification capacity of water quality indicators in various river reaches in winter

<table>
<thead>
<tr>
<th>Meandering reach</th>
<th>s</th>
<th>−R (DO)/km</th>
<th>R (TN)/km</th>
<th>R (NH₃-N)/km</th>
<th>R (TP)/km</th>
<th>R (CODₜ)/km</th>
</tr>
</thead>
<tbody>
<tr>
<td>15−17</td>
<td>1.56</td>
<td>0.14</td>
<td>0.19</td>
<td>0.00</td>
<td>0.26</td>
<td>0.16</td>
</tr>
<tr>
<td>13−15</td>
<td>1.22</td>
<td>−0.24</td>
<td>−0.31</td>
<td>0.01</td>
<td>−0.06</td>
<td>−0.08</td>
</tr>
<tr>
<td>10−13</td>
<td>1.30</td>
<td>0.12</td>
<td>−0.05</td>
<td>−0.04</td>
<td>−0.17</td>
<td>0.03</td>
</tr>
<tr>
<td>8−10</td>
<td>1.65</td>
<td>−0.10</td>
<td>−0.05</td>
<td>0.04</td>
<td>0.00</td>
<td>−0.06</td>
</tr>
<tr>
<td>7−8</td>
<td>1.02</td>
<td>0.13</td>
<td>0.10</td>
<td>−0.15</td>
<td>0.05</td>
<td>0.03</td>
</tr>
<tr>
<td>4−7</td>
<td>1.84</td>
<td>0.38</td>
<td>0.04</td>
<td>0.15</td>
<td>−0.02</td>
<td>0.14</td>
</tr>
<tr>
<td>2−4</td>
<td>1.14</td>
<td>−0.30</td>
<td>−0.14</td>
<td>−0.09</td>
<td>0.30</td>
<td>−0.07</td>
</tr>
<tr>
<td>1−2</td>
<td>1.00</td>
<td>−0.38</td>
<td>0.21</td>
<td>−0.08</td>
<td>−0.12</td>
<td>−0.08</td>
</tr>
</tbody>
</table>

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Table 3 | Self-purification capacity of water quality indicators in various river reaches in spring

<table>
<thead>
<tr>
<th>Meandering reach</th>
<th>s</th>
<th>−R (DO)/km</th>
<th>R (TN)/km</th>
<th>R (NH₃-N)/km</th>
<th>R (TP)/km</th>
<th>R (CODₜ)/km</th>
</tr>
</thead>
<tbody>
<tr>
<td>15−17</td>
<td>1.56</td>
<td>0.607</td>
<td>0.21</td>
<td>0.11</td>
<td>0.17</td>
<td>0.30</td>
</tr>
<tr>
<td>13−15</td>
<td>1.22</td>
<td>−0.04</td>
<td>−0.08</td>
<td>0.00</td>
<td>0.19</td>
<td>−0.21</td>
</tr>
<tr>
<td>10−13</td>
<td>1.30</td>
<td>−0.15</td>
<td>0.03</td>
<td>0.02</td>
<td>0.13</td>
<td>0.05</td>
</tr>
<tr>
<td>8−10</td>
<td>1.65</td>
<td>0.60</td>
<td>−0.14</td>
<td>0.07</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>7−8</td>
<td>1.02</td>
<td>−0.52</td>
<td>−0.27</td>
<td>−0.17</td>
<td>−0.07</td>
<td>0.01</td>
</tr>
<tr>
<td>4−7</td>
<td>1.84</td>
<td>0.48</td>
<td>0.26</td>
<td>0.08</td>
<td>0.19</td>
<td>0.02</td>
</tr>
<tr>
<td>2−4</td>
<td>1.14</td>
<td>−0.404</td>
<td>0.21</td>
<td>0.07</td>
<td>0.04</td>
<td>0.13</td>
</tr>
<tr>
<td>1−2</td>
<td>1.00</td>
<td>−0.03</td>
<td>−0.13</td>
<td>−0.01</td>
<td>−0.06</td>
<td>−0.17</td>
</tr>
</tbody>
</table>
microorganisms (Kim et al. 2003). Therefore, temperature becomes the limiting factor for phosphorus removal and it is difficult for other factors, such as the increased DO and the decreased water flow velocity due to the river.
meandering, to take effect. Although the increased DO growth rate is expected to enhance the oxidative decomposition of organic matter and the reduction rate of CODCr, the monitoring results show contrasting behaviour, which may be caused by the biological or other unknown parameters. This result shows that sinuosity is not the only factor that determines water quality. We are conducting biological surveys and laboratory experiments related to microorganisms to verify the correlation between river sinuosity, biology and water quality.

Within a river basin, an increase in river sinuosity increases the actual length of river, which elongates the action time of the river’s other basic self-purification factors; for example, the vertical hyporheic exchange flows between the river water and groundwater, the purification achieved through the contact with plants on river banks, as well as the decomposition of pollutants catalysed by light. The process in which the pollutants are affected by river sinuosity is shown in Figure 4, the increase of sinuosity affects the intermediate factors (DO, flow velocity, etc.), which leads to the decline of water quality indicators.

Observations of the turning point (positive value to negative value) of the reduction rate of each water quality indicator indicate that when the river sinuosity is above 1.42, the nitrogen and phosphorus pollutants enter the reduction state, while DO increases. Therefore, without regard to CODCr, we conclude that the sinuosity of the study river section should be at least 1.42.

In short, when other conditions are constant, straight river sections with a low level of sinuosity have a poor purification capacity with regard to pollutants, while a high level of river sinuosity improves the river’s self-purification capacity and thus the water environment. Therefore, in the urbanization renovation in the lower and middle reaches of the Yangtze River, we should be restrained from excessively straightening the rivers for the sake of flood control and high land utilization efficiency and should maintain an appropriate level of river sinuosity. Only in this way can the long-term health of the rivers be ensured, the river water quality be guaranteed, and the housing and living environment of residents be safeguarded.
CONCLUSIONS

In this study, we conducted field monitoring and analysis on the water quality of reaches of the Shiwuli River with different levels of sinuosity. Based on the field data, we established the correlation between river sinuosity and the self-purification capacity on each water quality indicator and also discussed the effect of river sinuosity on the reduction of pollutant concentrations. The conclusions are as follows:

(1) River sinuosity had significantly positive correlations with the growth rate of DO, the reduction rates of TN and NH₃-N, and the reduction rate of TP at high temperature, but no significant correlation with CODCr.

(2) Meandering river reaches showed a higher self-purification capability, due to the increased DO caused by the increase in sinuosity, the decreased water flow velocity, the intensified vertical hyporheic exchange flow, and the elongated action time of the river’s other basic self-purification factors.

(3) The threshold sinuosity is 1.42 to ensure pollutant reduction in the Shiwuli River.

The above findings could help the scientific planning of river reconstruction in the process of urbanization in the middle and lower reaches of the Yangtze River in China. In addition, we will further analyse the effects of river sinuosity on water quality through physical model experiments and numerical simulation experiments to enhance our studies.

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