Research on the water quality evaluation and nutrients removal efficiency of ecological ditch

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Abstract. Ecological ditches have a good effect on improving polluted runoff, and their removal efficiency and construction length play a decisive role in the implementation of ditches. Based on the field monitored data of Wulihu River, the water quality was evaluated by the comprehensive index method. Then, the removal efficiency of nutrients in the ecological ditch was studied, and the optimum lengths of ecological ditch for main pollutant removal were obtained. The results showed that the water quality gradually became better along the Wulihu River and the removal efficiency of chemical oxygen demand was the largest (60.52%). The optimum ecological ditch length for total nitrogen removal was 6.05 km and that of nitrate nitrogen, nitrite nitrogen, chemical oxygen demand were 29.45 km, 5.61 km and 6.92 km, respectively.

1. Introduction
Water is characterised by its recyclability and unique physicochemical properties, which is the condition of human survival as well as important material basis for production and living [1]. At a time of increasing water pollution problems that large numbers of rivers and lakes are polluted by human production, domestic wastewater and agricultural runoff [2].

Constructed wetland is derived from natural wetland, which has efficient removal efficiency on nitrogen and phosphorus pollutants [3, 4]. Ecological ditch, as a kind of constructed wetland, can remove the nitrogen and phosphorus, with removal efficiencies up to 83% and 88%, respectively [5]. Some foreign studies have shown that the ecological ditch is the best management measure in the control of agricultural non-point source pollution and an indispensable component of the agricultural production landscape [6]. The nutrients removal function of wetland is significant correlation with landscape structure metrics, including the “Distance source to centre (the treatment distance of pollutant in the wetland)”[7]. In addition, the purification of wastewater through wetlands must be characterized by ecology, high efficiency and low investment[8, 9], so the study of nutrient removal efficiency in ecological ditch and optimal construction length has vital meanings for economy.
2. Materials and methods

2.1. Study area and sampling

![Figure 1. The Wulihu River and sampling points.](image)

The Wulihu River is located in Anhui province, China (116.21~116.24 E, 32.59~32.68 N), as an ecological ditch excavated artificially based on the natural river, which combines with ecological restoration, urban flood control and municipal landscape. The ecological ditch can be used to remove nutrients by near-nature planting emergent plants such as reed, lotus, and alternanthera philoxeroides and so on. The important hydrological parameters of this ecological ditch during the study period were shown in Table 1. The hydraulic residence time (HRT) of the study area was about 39.21 hours and the nutrients had enough time to be partially removed under this condition[10]. In this study, 10 sampling points including W1~W10 were set from upstream to downstream along the ditch. Starting from W1 (the inlet of water), the distances between the rest points and W1 were 1.49 km (W2), 2.10 km (W3), 2.83 km (W4), 3.88 km (W5), 6.22 km (W6), 7.13 km (W7), 7.48 km (W8), 7.63 km (W9) and 7.89 km (W10, the outlet of water). A total of three parallel water samples were collected at each sampling point. The indicators measured for each water sample included total nitrogen (TN), total dissolved nitrogen (TDN), ammonia nitrogen (NH₄⁺-N), nitrate nitrogen (NO₃-N), nitrite nitrogen (NO₂-N), total phosphorus (TP), total dissolved phosphorus (TDP), phosphates (PO₄³⁻-P), chemical oxygen demand (COD). The specific determination methods referred to the standard methods[11].

| Table 1. The hydrological parameters of Wulihu River. |
|----------------|----------------|----------------|----------------|
| Average width (m) | Average water depth (cm) | Average water velocity (cm/s) | HRT (h) |
| 20 | 298 | 5.59 | 39.21 |
2.2. Study methods

2.2.1. Water quality evaluation method. The comprehensive index method [12] was used to evaluate the water quality of the study area. The specific formulas are as follows:

\[ Q_j = \sum_{i=1}^n Q_{ij}, \]  
\[ Q_{ij} = \frac{C_{ij}}{C_{i0}}, \]

where \( Q_j \) is the water pollution comprehensive index of the \( j \)th sampling point, The lower \( Q_j \) value means the better water environment quality; \( Q_{ij} \) is the water pollution index of the \( i \)th indicator at the \( j \)th sampling point; \( C_{ij} \) is the measured values of the \( i \)th indicator at the \( j \)th sampling point; \( C_{i0} \) is the standard value (referencing the environmental quality standard of surface water in China) of the \( i \)th indicator.

2.2.2. Nutrient removal efficiency calculation. Under stable hydrological conditions, removal efficiency was generally determined by the change of nutrients concentration[13]. The removal efficiency of nutrients represents the environmental improvement capability of ecological ditches, which can be calculated by the following formula:

\[ e_i = \left( \frac{c_0 - c_1}{c_0} \right) \times 100\%, \]

where \( c_0 \) is the concentration of the \( i \)th indicator at the inlet, \( c_1 \) is the concentration of the \( i \)th indicator at the outlet, \( e_i \) is the removal efficiency of the \( i \)th indicator.

2.2.3. Statistical analysis and tools. In this study, the data processing was done using Excel 2010. Distribution maps were drawn by Origin 8.5. Correlation analysis and nonlinear fitting were completed by SPSS Statistics 22.0.

3. Results and discussion

3.1. Nutrients distribution

As showed in Figure 2, all forms of nitrogen decreased along the Wulihu River as a whole. TN decreased rapidly in the influent area, slightly increased at W4 and stabilized about 3.5 mg/L after W5. TDN decreased from 4.29 mg/L to 2.47 mg/L (from W1 to W3), but returned to 3.67 mg/L at W4, and then stabilized at about 3 mg/L. The concentration of NH\(_4\)-N fluctuated strongly in Wulihu River, the lowest was 0.02 mg/L at W3, the highest was 2 mg/L at W9, and the outlet concentration was higher than that at inlet. The NO\(_3\)-N gradually decreased along the water direction and the concentration decreased from 2.06 mg/L to 1.02 mg/L. The concentration of NO\(_2\)-N was trace and there was no obvious fluctuation in these sampling points, and the concentration was fell into the range of from 0.14 mg/L to 0.21 mg/L.

The distribution of various forms of phosphorus was similar to that of nitrogen, which also showed a decreasing trend in Wulihu River (see Figure 2). TP decreased from W1 to W3 and increased...
significantly at W4, and then decreased to 0.38 mg/L at W7 and increased to 0.50 mg/L again at the outlet. TDP decreased from 0.63 mg/L to 0.19 mg/L (from W1 to W7), but up to 0.36 mg/L at the outlet. The concentration of $\text{PO}_4^{3-}$-P fluctuated greatly, the highest was 0.32 mg/L at W1 and the lowest was 0.07 mg/L at W7, and then increased to 0.17 mg/L at W10.

COD had a decreasing tendency that its concentration reduced from 48.93 mg/L at W1 to 19.32 mg/L at W10. In particular, the concentration of COD increased significantly at W3 (53.24 mg/L) and W8 (34.84 mg/L). For the other sampling points, the concentration was basically stable at 20 mg/L after W5 (except W8).

3.2. Water quality evaluation

It can be observed in the chapter 3.1 that the distribution of water quality indexes will not be exactly the same. Therefore, the spatial change of water quality cannot be described scientifically using a single index. The comprehensive index method can consider all water quality indexes, so it was applied to the water quality evaluation of Wulihu River. The evaluation results of water quality were shown in Table 2.

Table 2. Water quality evaluation results of Wulihu River.

| Sampling points | W1  | W2  | W3  | W4  | W5  | W6  | W7  | W8  | W9  | W10 |
|-----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Q               | 1.75| 1.07| 1.16| 1.28| 0.99| 1.05| 0.84| 1.24| 1.18| 1.06|

It can be seen from the table 2 that the Q values of the water flowing through the Wulihu River reduced from 1.75 to 1.06. During this process, the water quality of W5 and W7 decreased significantly. The results of water quality evaluation suggested that Wulihu River, as an ecological ditch, had significant removal effect on nutrients. However, the fluctuation of water quality along the river also indicated that the removal efficiency of nutrients had some correlations with ditch length, but the correlations were not explicit. Therefore, the removal efficiency of various nutrients in the Wulihu River should be analyzed in detail.

3.3. Nutrients removal efficiency of ecological ditch

In order to study the relationship between the ecological ditch length and the nutrients removal efficiency, the nutrients with the total removal efficiency (from W1 to W10) as positive were selected to test the correlation with ditch length. The nutrients that the correlation coefficient $|r|>0.7$ were considered significant correlated, and then the nonlinear relationship between the ditch length and them was conducted to obtain the detailed curves.

3.3.1. The total removal efficiency. The total removal efficiency of various nutrients, calculated according to formula 3, was shown in Table 3. The removal efficiency of COD was the highest in Wulihu River, reached 60.52%, which indicated that this type of ecological ditch had a significant effect on organic pollutant removal. The lowest removal efficiency was $\text{NO}_2^{-}$-N (23.17%). It should be noted that the removal efficiency of $\text{NH}_4^{+}$-N was $-16.67\%$, but up to $98.66\%$ at W3. The cause of this phenomenon may be the openness of Wulihu River and exogenous pollution at W4, but the $\text{NH}_4^{+}$-N was still declining after W4, so it was also necessary to test its correlation with the ditch length of Wulihu River.

Table 3. The total removal efficiency of various nutrient.

| Indicators  | TN (%) | TDN (%) | $\text{NH}_4^{+}$-N | $\text{NO}_3^{-}$-N | $\text{NO}_2^{-}$-N | TP (%) | TDP (%) | $\text{PO}_4^{3-}$-P (%) | COD (%) |
|-------------|--------|---------|---------------------|--------------------|---------------------|--------|---------|-------------------------|--------|
| e (%)       | 44.30  | 32.49   | -16.67              | 50.60              | 23.17               | 38.42  | 42.33   | 47.41                   | 60.52  |
3.3.2. The correlation test. The correlation coefficients between indicators and ditch length (D) calculated by SPSS were shown in Table 4. The results showed that TN, NO₃-N, NO₂-N, COD had a significant correlation with D, and these four indicators were fitted with D using nonlinear method.

Table 4. The correlation coefficients between indicators and D.

| Indicators | TN    | TDN   | NH₄⁺-N | NO₃-N   | NO₂-N  | TP    | TDP   | PO₄³⁻-P | COD  |
|------------|-------|-------|--------|---------|--------|-------|-------|---------|------|
| D          | -0.810** | -0.44 | 0.556  | -0.960** | -0.0705* | -0.538 | -0.382 | -0.373  | -0.676* |

Note: * and ** represent significant correlations at 0.05 and 0.01 confidence degree, respectively.

3.3.3. The efficiency curve of nutrients removal. The nonlinear fitting curves between these four water quality indicators and ditch length were shown in Figure 3.

The value of $R^2$ represents that the agreement degree between actual values and fitting values, and closer to 1 means better fitting relationship. The fitting degree of NO₃-N and D was the highest ($R^2=0.9224$) and that of COD and D was the lowest ($R^2=0.5149$). According to the fitting curve of TN and D, the derivative of curve was 0 when the D value was 6.05 km and the TN concentration tended to be stable after 6.05 km, so the optimum ditch length of TN removal ($D_{TN}$) for the ecological ditch was 6.05 km. Similarly, $D_{NO₃-N}$ was 29.45 km, $D_{NO₂-N}$ was 5.61 km and $D_{COD}$ was 6.92 km.

4. Conclusions

Based on the evaluation of water quality in Wulihu River, the relationship between the length of ecological ditch and nutrients removal efficiency was researched. The following conclusions can be drawn.

1) The water quality evaluation results of each sampling point in the river indicated that the water quality gradually became better along the river and tended to be stable at last.

2) The Wulihu River, as an ecological ditch, had different removal efficiency for different nutrients in the study, of which the removal efficiency of COD was the largest and that of NH₄⁺-N was the smallest.
3) For different nutrients, the optimal lengths of ecological ditch were different. The results showed that $D_{\text{TN}}$ was 6.05 km, $D_{\text{NO}_3-\text{N}}$ was 29.45 km, $D_{\text{NO}_2-\text{N}}$ was 5.61 km and $D_{\text{COD}}$ was 6.92 km.

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References
[1] Abraham J, Dowling K, Florentine S 2017 Risk of post-fire metal mobilization into surface water resources: A review Science of The Total Environment 599 1740-1755
[2] Dalu T, Wasserman R, Tonkin J 2017 Water or sediment? Partitioning the role of water column and sediment chemistry as drivers of macroinvertebrate communities in an austral South African stream Science of The Total Environment 607 317-325
[3] Huang J, Jr R B R, Hagedorn C 2000 Nitrogen removal in constructed wetlands employed to treat domestic wastewater Water Research 34 2582-2588
[4] Raisin G W, Mitchell D S 1995 The use of wetlands for the control of non-point source pollution Water Science & Technology 34 177-186
[5] Wu Y H, Kerr P G, Hu Z Y, et al 2010 Eco-restoration: simultaneous nutrient removal from soil and water in a complex residential-cropland area Environmental Pollution 158 2472-2477
[6] Cooper C M, Moore M T, Bennett E R, et al 2004 Innovative uses of vegetated drainage ditches for reducing agricultural runoff Water Science & Technology 49 117-123
[7] Li X, Jongman R H, Hu Y, et al. 2005 Relationship between landscape structure metrics and wetland nutrient retention function: A case study of Liaohe Delta, China Ecological Indicators 5 339-349
[8] Rousseau D P L, Vanrolleghem P A, Pauw N D 2004 Constructed wetlands in Flanders: a performance analysis Ecological Engineering 23 151-163
[9] Brix H 1994 Use of constructed wetlands in water pollution control: historical development, present status, and future perspectives Water Science & Technology 30 209-223
[10] Zhang Y Y, Cao C L, Ren L J, et al 2016 Effect of Different Combined Substrate under Different Hydraulic Retention Time in Vertical Flow Constructed Wetlands Ecology and Environmental Sciences 25 292-299
[11] Walter W G 1998 APHA Standard Methods for the Examination of Water and Wastewater Health Laboratory Science 4 137
[12] Liu Y, Zheng B H, Qing F U, et al 2013 Application of Water Pollution Index in Water Quality Assessment of Rivers Environmental Monitoring in China 80 4
[13] Zhang S H, Xiao R L, Liu F, et al 2015 Interception Effect of Vegetated Drainage Ditch on Nitrogen and Phosphorus from Drainage Ditches Environmental science in China 36 4516-4521