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Impact of urban land-use change on surface water pollution

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ABSTRACT

The purpose is to guide the proportion of urban land use and the layout of facilities, fully understand the change of surface runoff caused by land use in urban development, and thus solve surface runoff pollution. City A is selected for experiment base, the land use nature and urban construction projects of grade demonstration area are specifically analyzed. Spearman's analytic hierarchy process can reflect the land use type and establish the type and layout of urban facilities. The influence of land use indexes on surface runoff water quality is studied qualitatively and quantitatively with redundancy analysis. Then, key indexes are selected and analyzed to determine whether land use structures can be reasonably planned, which provides an effective basis for rational planning of land use structures. The results show that urban construction has a positive effect on improving surface runoff water quality. Under moderate rainfall intensity, the influence of urban equipment indexes on runoff is the most obvious. The results show that, when the average rainfall intensity is moderate rain, the surface runoff quality of the improved sample with the same properties is better than that of the unmodified sample.

Keywords: Land-use change; Surface runoff; Water pollution; Urban facilities

1. Introduction

With the accelerated global urbanization, the aggravating water resource destruction needs an urgent solution. Various studies have shown that the urban population and the population density are rising, and urban buildings are expanding, so land reuse and space recombination are eventually leading to changes in the cities' surface structure, breaking the balance of surface radiation, the original urban water cycle, and water resource utilization system [1].

Land-use change has a very complex impact on urban water resources. Rainfall-runoff changes with rainfall amount, rainfall intensity, and land use characteristics. The original urban surface has gradually changed from land and sand to hard soil, weakening the heat and water exchange between the ground and the atmosphere. Thus, the amount of rainwater flowing into the underground has been reduced, and the water absorbability of the surface has been declined [2]. Studies have shown that only one-fifth of rainwater is used as runoff in the large environmental system. In highly urbanized areas, urban roads are almost non-permeability for rainwater, and such roads are also increasing, with almost four-fifths impermeable rainwater [3]. The spread runoff enters the urban drainage system, and floods generally occur if the amount of rainwater accumulated exceeds the capacity of the urban drainage infrastructure. Meanwhile, rainwater runoff may be polluted by the hardening urban road surfaces. The initial rainstorm loss will wash away useless things, automobile exhaust, dust, and silt on impermeable roads, such as motorways and open areas. Pollutant sediments are eventually discharged into the water body, when harmful substances to the human body exceed the range of self-purification capacity of tap water, the nature of water will change badly [4].

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Here, the impact of land use on surface runoff is studied after urban infrastructure construction. First, in the practice of urban planning and design, the influence of land-use change on surface runoff is discussed, and the key land use indexes for controlling surface runoff are summarized. Second, an analysis is conducted on how to solve the quantitative structural relationship within these indexes to control runoff and runoff water quality. The results provide a reference for similar places in the future to restrict the number and location of urban facilities in urban development and help effectively manage the water ecological cycle and water resource utilization [5].

2. Method

2.1. Runoff data acquisition

Here, the measurement method is used for runoff data and runoff water sample data collection. Sample data are collected at city A's rainwater outlets because rainwater runoff is the total runoff from different catchment areas, representing land use [6]. For the runoff into the river, a flowmeter is installed at the outlet of each sampling point to continuously obtain the hourly rainwater runoff of the sampling point. Meanwhile, 2~3 connected tanks are selected as runoff sampling points at each sampling point [7]. After the formation of surface runoff, the rainwater collector collects surface runoff samples every 10 min, 5 times per hour. Then, 40 flow monitoring points and 45 water quality sampling points are set. Runoff data is 5,800, water quality sampling data is 1,400. All data must be dimensionless to avoid deviations caused by different dimensions in statistical results. To avoid the influence of different basins and different rainfall levels, the runoff modulus coefficient is selected to reflect the size of runoff, which can be transformed into a dimensionless runoff coefficient, and the runoff and rainfall of rainfall are considered at the same time [8,9]. Due to the correlation, diverse types of rainfall are selected to study. Here, many indexes, including suspended solids (SS), biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), ammonia nitrogen (NH_3–N), and total phosphorus (TP) are selected to reflect the runoff pollution degree. The Grubbs test can screen and eliminate the small anomalies below the water level, and the average content of each index in rainfall-runoff is finally obtained [10].

2.2. Acquisition of land use data

Here, the urban land use situation in 2020 is drawn with computer-aided design (CAD) ground buildings, and the urban base coverage information is obtained through statistical data and manual interpretation. According to foreign concepts of building permeability and effective impervious area, land use structure can be divided into effective impervious area (EIA) and ineffective impervious area (IIA) [11]. IIA includes green space and underwater impervious surfaces. The underground impervious area includes the roof green design, permeable road, and water body. Environmental assessment means that the impervious area is directly connected to the drainage collection system through rainwater pipelines [12]. Compared with impervious surfaces, environment assessment contributes more to urban area runoff. IIA is a city facility in Area A that cuts off drainage collection systems in impervious areas. Environmental assessment and environmental impact jointly constitute the total impervious area.

2.3. Land use classification

To determine the influence of land use on surface runoff and runoff water quality, the research scope should be determined first. According to the development trend of watershed systems, the water quality grade of area runoff and the first-level runoff are selected for watershed division [13]. City A is a plain river network city, the drainage network of different land types is directly connected with the river, so each plot is a separate watershed. Here, the value of land use zoning in different regions are obtained through the Excel software and Sutherland classical equation, and Sutherland classical equation can calculate the site environmental impact assessment rate, which applies to the problem of small watersheds (8–28 ha) according to the U.S. Geological Survey [14]. The specific method is shown in Fig. 1. The sample points for transformation are determined based on the construction drawings of water absorption facilities at each point, combined with the actual needs of change, and according to the classification criteria in Fig. 1 [15]. The anti-seepage area of residential and multi-person buildings is partially disconnected from the drainage collection system, the anti-seepage area of the park is highly disconnected from the drainage collection system, and the anti-seepage area of each block is connected to the drainage collection system.

3. Effect of land use on surface runoff water quality

3.1. Redundancy analysis results

The sample data redundancy is analyzed through the CANOC05.0 software. Firstly, the trend result analysis can determine the linear relationship between the dependent variable and the independent variable [16]. If the gradient value of the first axis in the four axes is greater than 4, the corresponding analysis model is selected; if the gradient value is less than 3, redundancy analysis is selected; if the gradient value falls between 3 and 4, then both methods are applicable [17]. After calculation, the slope of the first axis is 0.498, far less than 3, indicating that the water quality index is linear with the land use index [18]. Therefore, a redundant analysis method is selected, and the relationship between land use and water quality is shown as the arrow of land use index and water quality index (Fig. 2), the length and angle of the arrow in the figure indicate that water quality indexes have different responses to land use indexes [19]. The longer the length is, the greater the angle is (sharp angle means that land use is positively correlated with water quality indexes, while blunt angle means a negative correlation). The higher the value is, the greater the correlation between the two is, and the lower the value is, the lesser the correlation is.

Fig. 2 displays that the types of land use indexes affecting the runoff water quality of each sample are significantly different. The reconstructed public building samples (R01–R06) are mainly affected by the IIA ratio. Park samples

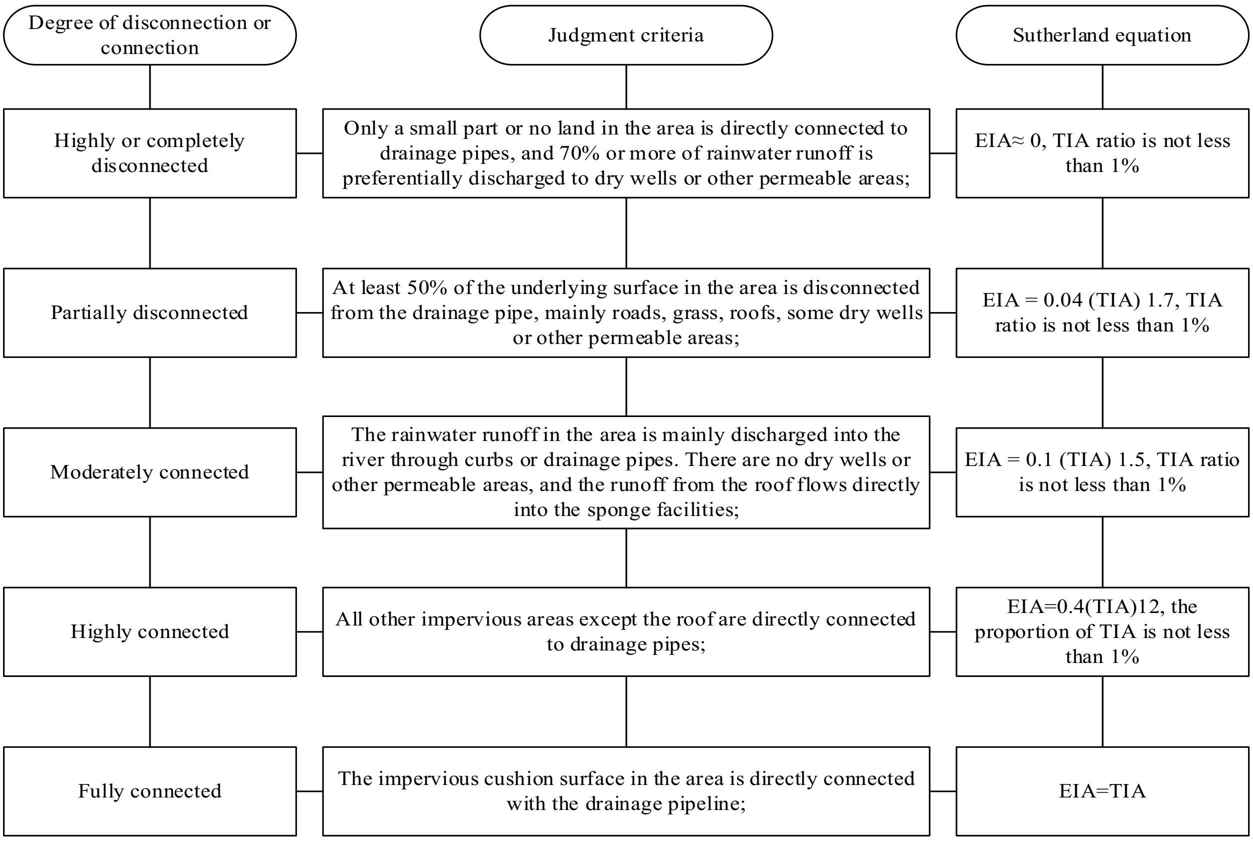

Fig. 1. EIA is obtained by Sutherland Equation.

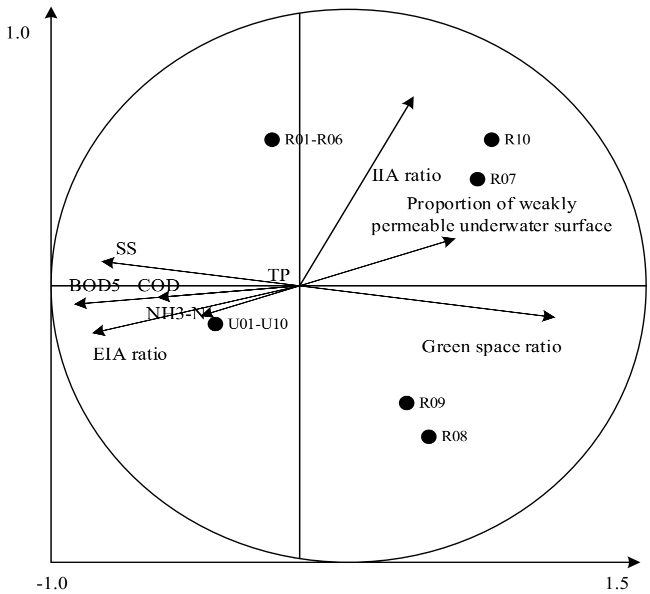

Fig. 2. Redundancy analysis of land use index and water quality indexes.

(R08 and R09) and park samples (R07 and R10) are significantly affected by the green space ratio and underwater ratio. Unmodified samples (U01–U10) are mainly affected by green space rate and environmental assessment on impervious surfaces. Environmental impact assessment of construction land is the main index of increased runoff pollution load. Green space rate, underwater impervious surface rate, and IIA are negatively correlated with the water quality index [20]. The correlation between green space rate and water quality index is the largest, indicating that the interception degree of green space on runoff pollution load is higher than the other two indexes. Land use had significant effects on SS, BOD, COD, and NH_3–N, while TP had no significant effect on land use [21]. The correlation between the EIA ratio and water quality, and between IIA ratio and water quality indexes are compared. The results show that the EIA ratio and IIA ratio have opposite impacts on water quality indexes, and the correlation between environmental impact assessment and water quality indexes is higher than that of IIA.

3.2. Partial least squares regression analysis results

The partial least squares (PLS) regression model is established by SIMCA-P software, and the automatic adaptation analysis is clicked to adapt the model. Two local least squares components are extracted by the cross-validation principle of the software. The information utilization rate of the *X* model is R^2X (cum) = 0.942, and the interpretability of *R* is R^2Y (cum) = 0.828. The cross-validity value Q^2 (cum) = 0.7819, Q^2 (cum) is cross validity, indicating that the PLS regression model has high prediction accuracy for new data. Q^2 (cum) > 0.5 indicates that the model has high prediction accuracy. When Q^2 (cum) < 0.05, the model is not significant.

Fig. 3 illustrates that the updated plots are mainly affected by the ratio of green space, IIA, and underwater impervious surface. RO1–R04 is mainly affected by the proportion of IIA in impervious surfaces, R07–R09 is mainly affected by the proportion of green space. The representative water quality indexes are SS, BOD_5, COD, and NH_3–N, which are influenced by the environment impact assessment.

Some empirical equations for the ratio of water quality indexes to land use indexes are calculated through PLS regression. These equations are greatly influenced by soil types. The specific calculation is expressed as in Eq. (1).

$$f(x) = \alpha_p + \sum_{p=0}^{n} \left(\mu_p \times \beta_p \right) \tag{1}$$

where $f(x)$ stands for water quality index concentration (mg/L), α_p represents a constant of p land use index on water quality indexes, μ_p denotes the level p land-use impact index, and β_p is the p land use index (%).

The influence degree of different land-use indexes on water quality indexes is shown in Fig. 4, and the influence order is as follows: green space rate > EIA ratio > IIA ratio > underwater seepage control rate. Specifically, SS is significantly affected by four land-use indexes; BOD_5 and COD are mainly affected by green space rate and environmental impact assessment; the change of NH_3–N caused by the land-use index is less significant than that caused by other water quality indexes, indicating that land-use index is not the most significant index affecting the average concentration of NH_3–N [22]. Generally speaking, the higher the EIA ratio is, the higher the average concentration of pollutants is, and the worse the water quality is. The larger the proportion of green space is, the worse the permeability of IIA underwater surface is, the poorer the permeability of the IIA underwater surface is, the lower the average content of pollutants that are more harmful to the human body, and the better the water quality is. When rainfall occurs, it is difficult to form surface runoff when the rainwater in the inflow areas, such as green space and permeable roads infiltrates into the ground. If the pollutant is overweight, it will not rush into the river through the drainage network. Although IIA is an impermeable area, it is not connected to the drainage pipe or its surface. Runoff mainly flows to the nearby water absorption facilities, rather than directly into the drainage ditch. Therefore, the EIA rate can be reduced with the increase in the proportion of green space and permeable roads in construction land and the introduction of impervious road runoff into sponge facilities, such as green space, which controls land runoff pollution and improves river water quality.

The influence of the land use importance index on the water quality index can be expressed as a variable of important prediction index (VIP) (Fig. 5). According to the VIP ranking table, the VIP value of green space environmental impact assessment is greater than 1, the characteristic ratio is

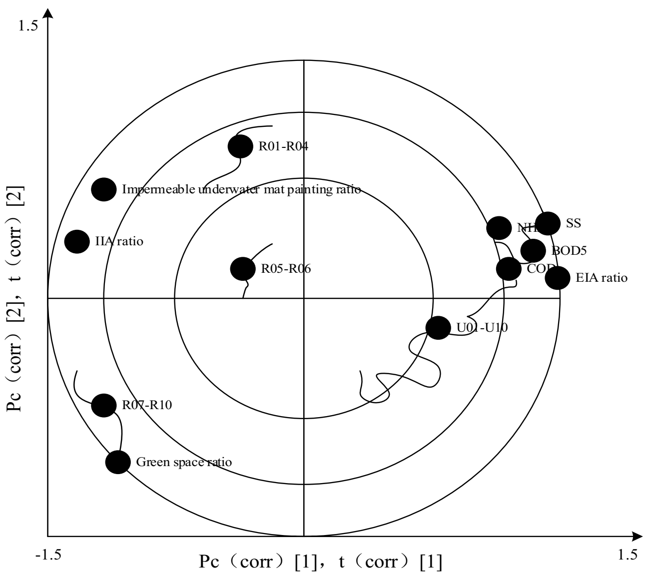

Fig. 3. Impact load diagram of land use types on different drainage zones.

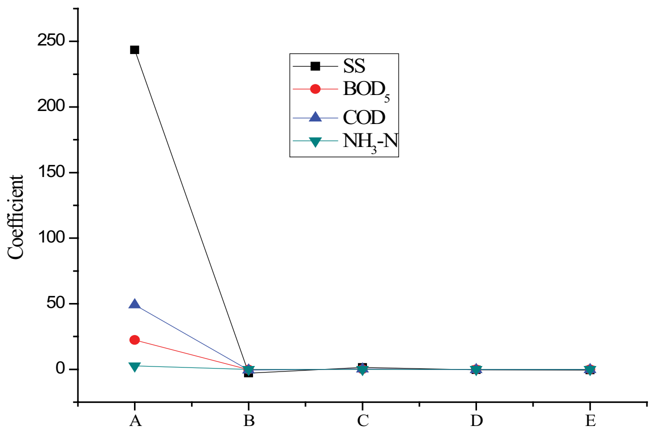

Fig. 4. The influence coefficient of land use on water quality indexes.
Note: A-Constant; B-Green space ratio; C-EIA ratio; D-Proportion of weakly permeable underwater surface; E-IIA ratio.

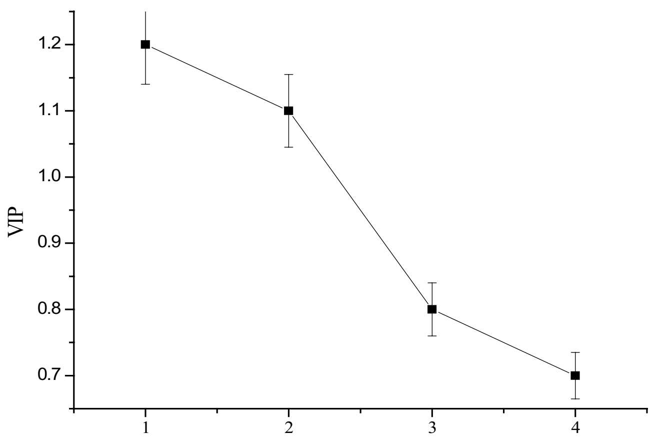

Fig. 5. Ranking of VIP values of land use indexes affecting water quality.
Note: 1-Proportion of green space (%); 2- EIA (%); 3-IIA ratio (%); 4-Proportion of impermeable underwater surface (%).

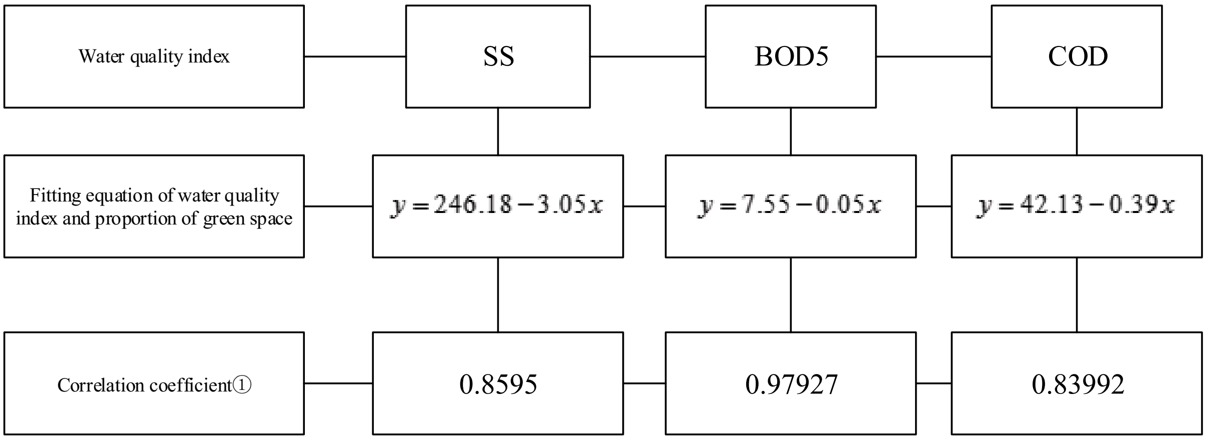

Fig. 6. When EIA ≈ 0, the regression prediction of SS, BOD_5, COD, and the proportion of green space.
Note: ① The closer the correlation coefficient is to 1, the closer the fitting result is to the data to be fitted, and the better the fitting result is.

between 0.8–1, and the ratio of green space to the impervious surface is less than 0.8, indicating that green space environmental impact assessment has an impact on water quality index, which has important explanatory significance. The green space environmental impact assessment and characteristic ratio are the key indexes affecting water quality.

3.3. Origin fitting prediction results

To control the relationship between land use types and surface runoff water quality, the fitting relationship between the land use indexes and surface runoff water quality is constructed through the original point fitting equation, and the surface runoff water quality is envisaged in advance.

According to the analysis results of the PLS regression method (Fig. 6), the EIA ratio on the X-axis and the average concentrations of SS, BOD_5, and COD on the Y-axis is obtained. According to the disconnection or connectivity between the impervious area of the sample and the drainage network, nine fitting equations are established with Origin2017 software. The green land is set as the X-axis, combined with the other three water quality indexes, three fitting equations are established. According to the obtained sample data, it is predicted that, under the middle gradient rainfall, the conversion level of different runoff water quality can reach surface water IV, and the scope of secondary standards of sewage discharge should be controlled, as well as the land use indexes.

Based on the redundancy analysis, the influence of runoff water quality index on different land types is discussed qualitatively. In land-use indexes, the environmental impact assessment rate is significantly and positively correlated with water quality indexes, such as green space, water permeability, and IIA. The proportion of green space is negatively correlated with each water quality index, and the correlation between green space proportion and each water quality index is the strongest. According to the PLS analysis, the influence of land use indexes on the surface runoff water quality indexes from large to small is as follows: green space rate > environmental impact assessment rate > IIA rate of underlying surface > seepage prevention rate. Finally, the origin fitting equation can predict the response threshold of surface water in class IV and the environmental impact assessment rate of green space, the surface water quality grade, and the secondary sewage discharge standard.

4. Conclusions

Here, the influence of construction land types on urban surface runoff water quality is analyzed, and specific influential mechanisms are concluded. Based on redundancy analysis, the relationship between land-use types and runoff water bodies is revealed. Land use index will affect runoff water quality, greening activities, impervious surface, and water quality index is negatively correlated, environmental impact assessment rate and water quality index is positively correlated. Soil SS, BOD_5, COD, and NH_3–N are related to land-use indexes. Based on PLS regression analysis, the influence of different land-use areas on the water quality index is quantitatively discussed. The key indexes affecting water quality are the green space rate and environmental assessment rate. The indexes affecting urban water quality are SS and BOD_5.

Through various analysis methods, the impact of land-use change on surface runoff of urban small watersheds is studied qualitatively and quantitatively. Although some achievements have been made, there are still some shortcomings that need further research and improvement. Because the monitoring data of surface runoff and surface runoff water quality is not enough, the number of selected rainfall types is insufficient, and the statistical law is insufficient, the final calculation results may produce some deviation. In future research, it can be considered to increase the sufficient amount of experimental data, further expand the research scope, and make the results of the calculation model more accurate. The impact of underground runoff is complex. Here, the land-use change is only studied from the perspective of underlying surface permeability, other land-use change indexes do not consider the use of permeable pavement and permeable pavement, which may lead to the impermeable facilities being classified into the same underlying surface. Therefore, the analysis index of the underlying surface can be further improved, and the statistical results can be closer to the actual situation.

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