Ecological Remediation Measures for Non-point Source Pollution Based on Source-Sink Landscape Theory: A Case Study of Huanghou Basin

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Abstract The growth of society and population has led to a range of water pollution issues. Among these, non-point source pollution assessment and treatment pose a particular challenge due to its formation mechanism. This has become a focal point and challenge in water pollution treatment research. The study area for this research was the Huanghou basin in Guizhou Province, southwest China. The land use type of the basin was analyzed using remote sensing technology, and water quality data was collected by distributing points throughout the basin, based on source-sink landscape theory. The distribution map of the basin's source-sink landscape and the results of water quality data accurately and efficiently identified the areas with high risk of non-point source pollution in the western and southwestern residential and agricultural areas of the upper basin. Hence, a strategy of "increasing sinks and decreasing sources" was proposed. The strategy was implemented at both macro and micro levels to address non-point source pollution in the basin using ecological remediation techniques. The work to control karst rocky desertification should continue at a macro level. The rocky desertification area in the basin should gradually transform into grassland and forested land, while increasing the overall area of the sink landscape. Ecological restoration techniques, such as slope planting, riparian zone vegetation restoration, increasing plant abundance, and restoring aquatic plants, can effectively control non-point source pollution at the micro level. Compared to traditional control methods, this remediation strategy focuses on source and process control. It is more effective and does not require large-scale water pollution control projects, which can save a lot of environmental control funds and management costs. Therefore, it has greater research significance and application value.

Keywords Source-sink landscape theory, Non-point source pollution, Ecological restoration, Rocky desertification control, Karst basin
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Water is a vital resource for all life, including human beings, and is crucial for human production and survival. As a result, water pollution has long been a significant obstacle to the world's sustainable development[1-2]. Since the 1960s, non-point source pollution has become increasingly recognized as a serious issue. As a result, the international environmental community has placed great emphasis on researching and managing non-point source pollution. Controlling non-point source pollution in a basin has become a crucial task in water environment management. Point source pollution, on the other hand, mainly originates from industrial wastewater and urban domestic sewage, with clear sources and relatively simple treatment, as opposed to non-point source pollution. Non-point source pollution is characterized by random sources, wide distribution, and strong latency. Assessing and treating non-point source pollution in basins can be challenging due to the uncertainty surrounding its formation mechanism[3]. Since the 1970s, numerous studies have demonstrated that landscape configuration impacts non-point source pollution in rivers[4]. Therefore, exploring non-point source pollution at the landscape level is becoming a popular trend. This approach provides basin management decision-makers with a multifaceted perspective on preventing and managing water quality pollution.

The source-sink theory originated in the field of environmental science and was initially applied to the study of global change and the atmosphere[5]. In 1988, Pulliam[6] was the first to apply source-sink theory to animal population ecology. Chen et al.[7] founded the theory of source-sink landscape by combining ecological process research with landscape model research and introducing source-sink theory into landscape ecology. According to the theory, the spatio-temporal dynamics of landscape material changes involve sources and sinks. A source is a landscape type that promotes ecological processes, while a sink is a landscape type that hinders them. Due to changes in the surrounding environment and ecological processes, the source and sink will alternate with each other. Practical research must analyze the classification of source and sink landscape types based on the research background. Fig.1 shows that, when studying non-point source pollution, source landscapes are those that cause pollution to water bodies. These include agricultural land with high fertilizer application rates and residential areas with concentrated output of domestic waste. Forested lands, grasslands, and wetlands are typical sink landscape types that absorb pollutants and slow down their development.

The theory of source-sink landscapes is applied to identify non-point source pollution in basins. Ecological restoration is then utilized to control the development trend of non-point source pollution in basins. At the macro level, the spatial layout of source-sink landscapes in basins with significant non-point source pollution is regulated to induce a reasonable layout of source-sink landscapes in the region. This allows nutrients to reach an equilibrium state before entering the water body, thereby controlling non-point source pollution. Ecological remediation is carried out at the micro level in areas with serious non-point source pollution through the interception and absorption of plants. Compared to traditional control methods, this remediation strategy focuses on source and process control. It is more effective and does not require large-scale water pollution control projects, which can save a lot of environmental control funds and management costs. Therefore, it has greater research significance and application value.

1 Overview of the study area

The study area is situated in the Huanghou

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karst underground river basin, which spans across Dushan County and Libo County in southwestern China (Fig.2). The outlet of the underground river is located at 107°41' E, 25°16' N. The study area encompasses 27,825 hm^2 and is characterized by karst geomorphology and a well-developed groundwater system. The Huanghou basin comprises one main stream and 17 larger tributaries, which account for approximately 95% of the total basin area. The basin experiences a warm and humid subtropical monsoon climate, with an average temperature of 15 °C over multiple years, an average annual rainfall of 1,346 mm, and a frost-free period of up to 250 d. Rainfall is distributed unevenly throughout the year, with the rainy season occurring from April to September and accounting for approximately 75% of the annual precipitation.

The region experiences a dry season from October to March, during which only 25% of the annual rainfall occurs. Conversely, the summer season is marked by heavy rainfall, with a maximum daily precipitation of 160 mm. The study area has experienced a variety of human activities, including industrial operations, agriculture, urbanization, and tourism.

2 Source-sink landscape distribution in Huanghou basin

The Landsat image data and 30 m resolution digital elevation model (DEM) for the study area were obtained from Geospatial Data (http://www.gscloud.cn). The Landsat data underwent preprocessing, which included radiometric calibration, rapid atmospheric correction, and image fusion. The study area boundaries were delineated using visual interpretation, followed by land use classification. Based on China's land use classification standard[8], the area was categorized into five major types: agricultural land, residential land, forested land, grassland, and bare land. According to the source-sink landscape theory, agricultural land, residential land, and bare land were classified as source landscapes, while forested land and grassland were classified as sink landscapes. The study analyzed non-point source pollution in the basin using source-sink landscape distribution and implemented key governance measures. Ten sampling points were deployed from upstream to downstream in the Huanghou underground river basin based on historical information and on-site field investigations. From January to November 2022, field surveys and water quality sampling were conducted in the basin to monitor water quality indicators, including total phosphorus, total nitrogen, and ammonia nitrogen. The water quality indices for total phosphorus, total nitrogen, and ammonia nitrogen were determined using different spectrophotometric methods. Total phosphorus was determined using ammonium molybdate spectrophotometry, total nitrogen was determined using alkaline potassium persulfate digestion ultraviolet spectrophotometry, and ammonia nitrogen was determined using nano reagent spectrophotometry.

2.1 Land use analysis

According to the research findings presented in Fig.3, the basin area is comprised of 1,114 hm^2 of residential land, 3,478 hm^2 of agricultural land, and 1,085 hm^2 of bare land, which represent 4.00%, 12.50%, and 3.90% of the total area, respectively. In addition, forested land covers 16,129 hm^2 and grassland covers 6,019 hm^2, accounting for 57.97% and 21.63% of the total basin area, respectively. Forested land is the dominant land use type and the main sink landscape, covering most of the basin and concentrated in the middle and lower reaches. The study area contains a concentration of major source landscape types in its upstream southwestern portion. The study area's western region is home to towns and cities that are the primary sources of domestic sewage and garbage in the basin. Cropland outside these urban areas is evenly dispersed and interspersed with grasslands and forested lands. The southwestern region of the study area comprises a cluster of villages with a high concentration of arable land. This area is particularly affected by fertilizer nutrient runoff into water bodies. Bare land is the crucial area for controlling rocky desertification in karst area. It is mainly concentrated in the middle reaches of the basin, away from settlements and farmland, and adjacent to grassland and forested land. Grasslands are widely distributed and dispersed throughout the basin. They have evolved from the original bare land.

2.2 Source-sink landscape distribution

The distribution map in Fig.4 shows that the proportion of sink landscape area (79.60%) is much higher than that of source landscape area (20.40%) in the study area. This indicates a generally low risk of non-point source pollution. The areas at higher risk for non-point source pollution are the western and southwestern portions of the upstream basin. These areas have significant source landscapes generated by population concentrations. The concentration of nutrients in water bodies has continuously increased due to domestic sewage from human life and fertilizers applied from farming activities. The water quality test results indicate that the average concentration of total nitrogen in the water body is 2-3 times higher in the source landscape area than in the sink landscape area. Similarly, the average concentration of total phosphorus is about 4-5 times higher in the source landscape area than in the sink landscape area. Additionally, the average concentration of ammonia nitrogen is up to about 10 times higher in the source landscape area than in the sink landscape area. Residential land use has a significant impact on factors related to water pollution, despite its limited size. Although the middle and lower reaches have extensive forested lands and grasslands that can effectively intercept upstream pollutants, the balance between the source and sink landscapes is gradually disrupted as the population grows. This exacerbates the risk of non-point source pollution in the lower reaches. Based on the spatial distribution map of source-sink landscapes in the study area, it is recommended that non-point source pollution management prioritize the western and southwestern areas of the upper basin.

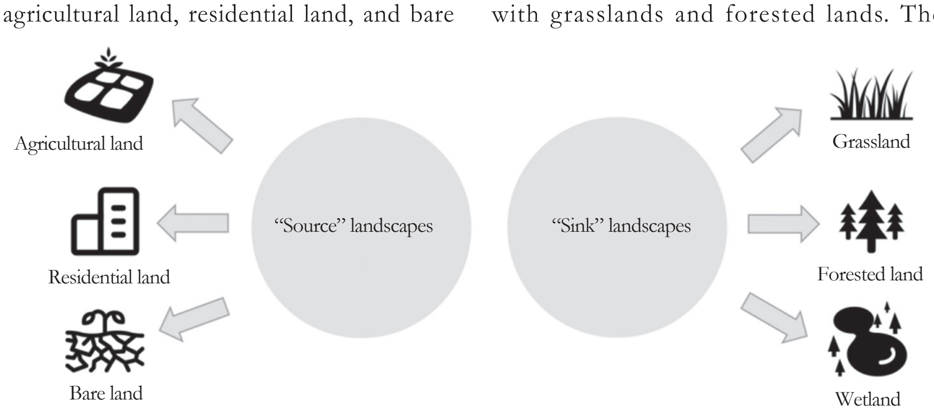

Fig.1 Classification of source-sink landscapes corresponding to land use types

3 Ecological restoration measures for controlling non-point source pollution

To mitigate the growing risk of non-point source pollution in the basin, experts proposed an ecological remediation strategy that involves increasing sinks and reducing sources. The study area is situated in a complex karst region known for its ecological intricacy and vulnerability, as opposed to a flat terrain[9]. The effective implementation of rocky desertification control in karst areas provides a viable approach to expanding the sink landscape in the basin. Rocky desertification control is primarily achieved through artificial tree planting, farmland restoration, soil improvement projects, small-scale water conservation facilities construction, and clean energy implementation in rural areas(Fig.5). Satellite images indicate that vegetation in karst areas of southwestern China has become significantly greener and biomass has increased[10]. This suggests that karst rocky desertification has been effectively controlled and demonstrates the potential for controlling non-point source pollution through such management measures. Non-point source pollution is controlled through plant ecological restoration at the micro level.

3.1 Slope planting

Vegetation restoration promotes the infiltration of surface runoff and effectively reduces the loss of pollutants from water bodies. Forested land has a significant effect on increasing subsurface runoff and reducing nutrient losses compared to wasteland[11]. The root system of the plant absorbs and intercepts pollutants, including inorganic harmful substances, toxic chemicals, and heavy metal elements present in the water body. Due to the topography and geomorphology of the karst region, various human and agricultural activities often occur, even in mountainous areas with steep slopes. These activities can directly exacerbate the potential for nutrient loss due to fertilizer application. The upper basin's southwestern region has a significant concentration of farmland and orchards, with much of the cropland located adjacent to hillsides. During the rainy season, runoff accelerates as rainfall increases, and rainwater scours the soil surface, carrying large amounts of fertilizers into lakes and rivers, causing a significant decline in water quality. Increasing vegetation cover on slopes can improve water quality by increasing the contact area between plants and stormwater, slowing down the runoff rate, and allowing plant root systems to absorb and intercept pollutants carried by the water (Fig.6).

3.2 Riparian zone vegetation restoration

In urban residential areas, impervious surfaces like roofs and sidewalks accelerate the rate of pollutant runoff. Increased residential land use also provides additional pathways for pollutants to run off (Fig.7). Construction has significantly damaged river ecosystems due to human disturbance[12]. Protecting riparian zones, which serve as a crucial link between terrestrial and aquatic systems[13], is essential for maintaining in-stream water quality. Riparian vegetation restoration plays a significant role in maintaining and improving stream water quality. Vegetation in the area reduces the concentration of pollution in the stream, making it an essential aspect of stream restoration efforts. Based on the water quality analysis, it was found that the upper part of the basin is situated in the town's residential areas, which have high levels of non-

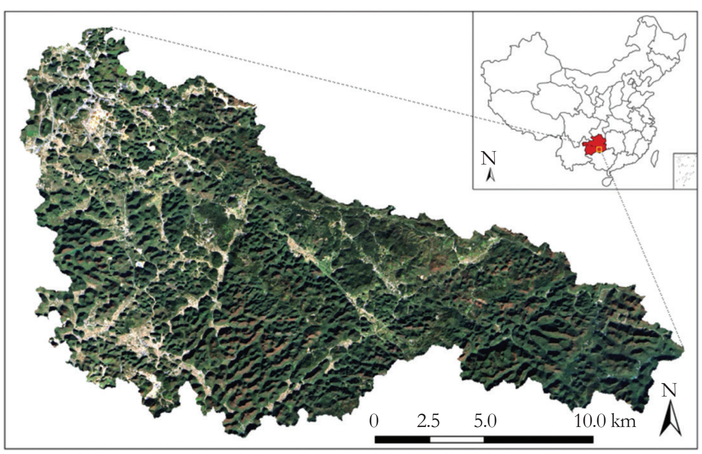

Fig.2 Location of the Huanghou basin in China

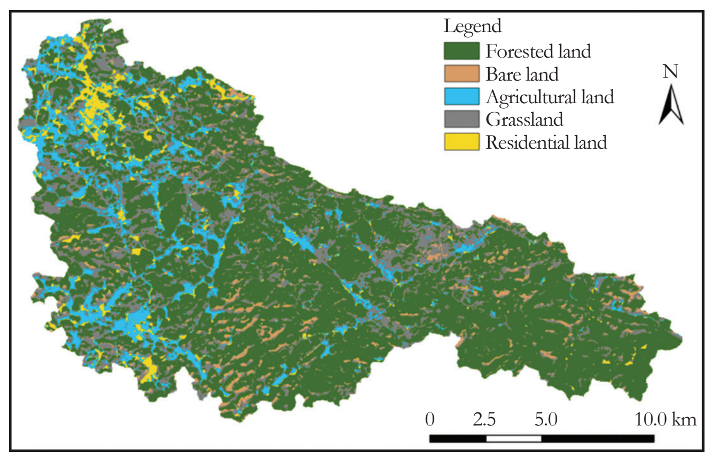

Fig.3 Spatial distribution of land use in Huanghou basin

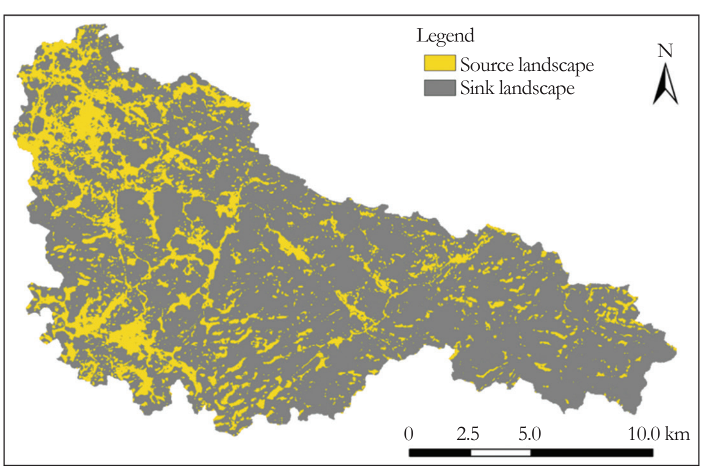

Fig.4 Spatial distribution of source-sink landscapes in Huanghou basin

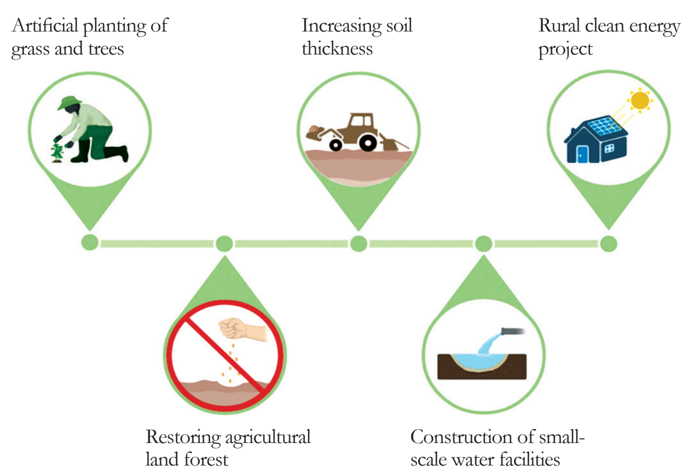

Fig.5 Related measures for controlling karst rocky desertification

point source pollution. Additionally, the town has a major stream that runs through residential areas on both sides. Without ecological protection in riparian zones, water bodies can carry pollutants from human activities into rivers, which can lead to water pollution. To address this issue, a variety of planting troughs can be designed to plant native plants and create ecological berms on traditional hardened slopes. When water carries pollutants into the river through the riparian zone, the plants on the berm can absorb and filter out some of the pollutants, reducing the degree of water pollution.

3.3 Increasing vegetation richness

Increasing plant abundance enhances the diversity of canopy structural features of vegetation (Fig.8), which in turn increases the area of vegetation that comes into contact with stormwater. This can effectively reduce the rate of runoff during heavy rainfall. Diverse plant root systems (Fig.9) play a crucial role in absorbing and intercepting nutrients in subsurface runoff and mitigating pollutants[14]. Different plants have varying abilities to absorb pollutants through their root systems. Additionally, the strength of the root system in improving the soil's resistance to erosion also varies. To improve water quality, a combination of mechanical functions such as adsorption, filtration, interception, and deposition, as well as biological functions such as infiltration and microbial degradation of the plants can be employed[15]. Moreover, the plant community consisting of trees, shrubs, and herbaceous plants can form a beneficial ecosystem. This ecosystem can control non-point source pollution and provide landscaping benefits.

3.4 Aquatic plant restoration

Aquatic plants play a crucial role in water ecosystems, as they have a significant impact on water quality. They can effectively reduce sediment content and control non-point source pollution by absorbing and filtering pollutants in the water. However, in environments with poor water quality, a large number of algae may attach to the surface of water plants, exacerbating the decomposition process. The decomposition of aquatic plants is a natural metabolic process that can purify water quality, absorb nutrients, and promote the water ecosystem. Large-scale hydrophytic decomposition can not only serve as a source of nutrients for the lake, but also lead to the deterioration of the water body by accelerating sedimentation and swamping processes in the lake[16]. Aquatic plants in transitional blooms have been found in the more turbid areas of the basin. This is due to the lack of human management and control, which has led to the decomposition of large numbers of aquatic plants. To control the decay process

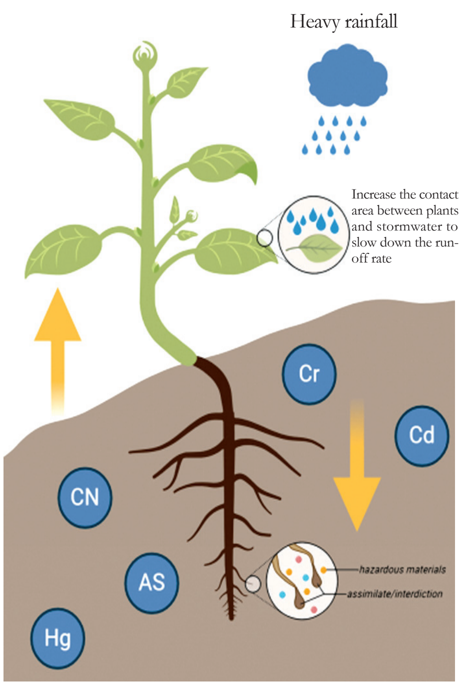

Fig.6 Slope plants improve water quality through canopy and root systems during heavy rainfall

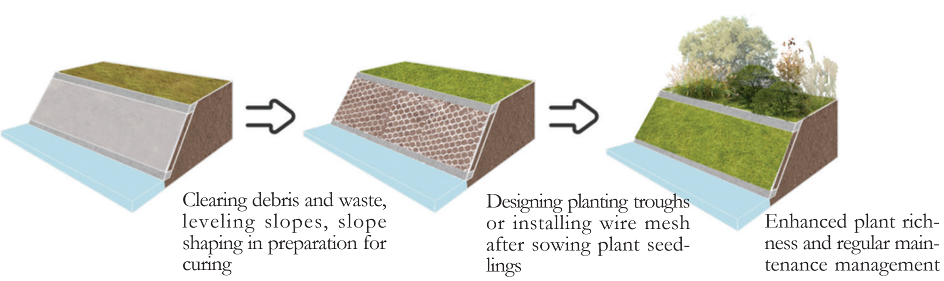

Fig.7 Ecological slope modification process

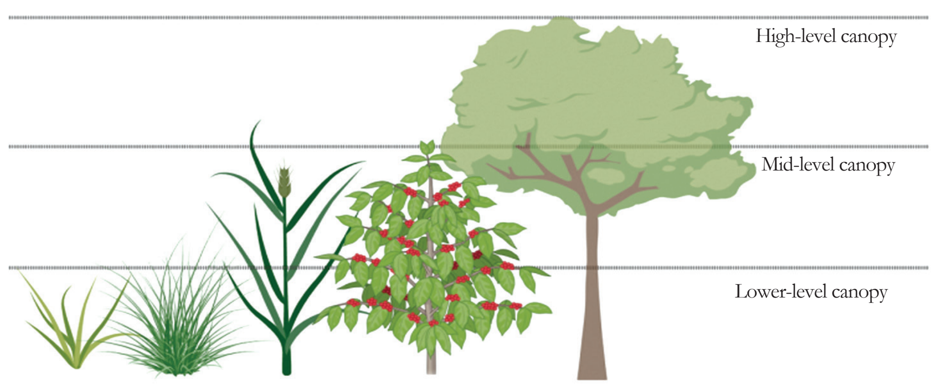

Fig.8 Classification of crown structure characteristics of different plants

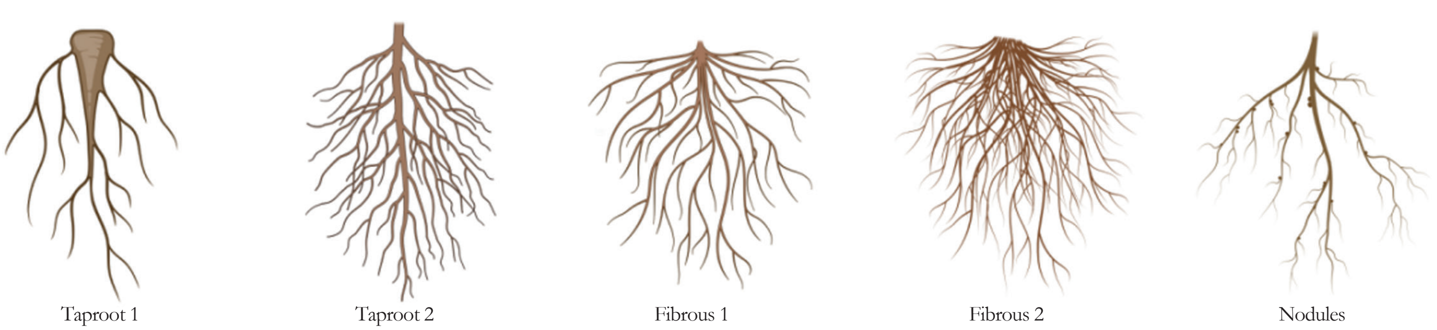

Fig.9 Different plant root types

of aquatic plants, it is often necessary to establish a virtuous aquatic ecological circulation system(Fig.10). Releasing certain local aquatic animals into areas with severe water pollution can impede algae growth and decelerate the decomposition of aquatic plants. The decayed material can then be utilized to nourish aquatic plants, achieving a harmonious balance that purifies water and prevents non-point source pollution.

4 Conclusions and discussion

Using remote sensing technology, we obtained the spatial distribution of the source-sink landscape in the Huanghou basin based on the theory of source-sink landscape. We then analyzed the trend of non-point source pollution risk in the basin. Extensive forested lands and grasslands are found in the middle and lower reaches of the Huanghou basin. They play a crucial role in protecting downstream water bodies as a typical sink landscape that absorbs and intercepts pollutants in water bodies. However, the upper reaches of the basin, which are located in residential and agricultural areas to the west and southwest, are the primary source landscape areas and are at a higher risk for non-point source pollution.

To manage non-point source pollution in the basin, the management idea of "increasing sinks and reducing sources" is adopted. Ecological restoration measures are taken to achieve this goal through a two-pronged approach at both the macro and micro levels. The work to control karst rocky desertification should continue at a macro level. The rocky desertification area in the basin should gradually transform into grassland and forested land, while increasing the overall area of the sink landscape. At the micro level, ecological restoration measures such as slope planting, riparian vegetation restoration, increasing plant richness, and aquatic plant restoration can effectively control non-point source pollution.

Currently, with the robust advancement of the source-sink landscape theory in the field of landscape ecology, research on assessing non-point source pollution in the basin based on this theory has become relatively comprehensive. However, research on preventing and treating non-point source pollution in the basin during later stages remains relatively inadequate and requires further study.

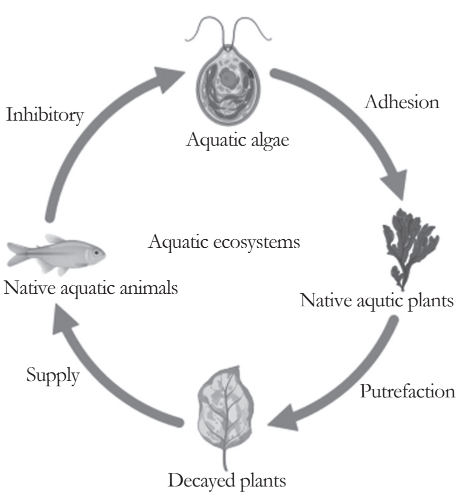

Fig.10 Good water ecosystem circulation mechanism

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