Research Progress on the Coupling Mechanism between Watershed Soil Erosion and Water Quality Evolution

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Abstract: The interplay between soil erosion dynamics and water quality degradation is a core scientific issue in watershed environmental management and ecological conservation. This paper systematically reviews the fundamental theories of hillslope runoff sediment transport capacity and soil detachment process dynamics, elucidates the watershed erosion-water quality coupling mechanism from two dimensions of sediment-nutrient coupled transport and multi-scale coupling simulation, summarizes the regulatory pathways governing land use and the multiple effects of "erosion reduction, sediment interception and pollutant purification" achieved by soil and water conservation measures, and focuses on the regional characteristics of arid and semi-arid areas on the Loess Plateau (represented by the Zuli River Basin) to analyze deficiencies of existing research and future directions. Studies show that sediment is the primary carrier of pollutant migration, and its transport process is comprehensively controlled by runoff hydrodynamics, soil properties and near-surface characteristics; optimization of land use structure can synergistically regulate water quality by altering erosion dynamics and transport pathways; soil and water conservation measures are critical means for erosion control and water quality improvement. To deliver solid scientific support for watershed ecological conservation and foster sustainable regional socio-environmental development, future studies need to deepen explorations of two core areas: multi-scale coupling processes in arid and semi-arid watersheds, and the water quality impacts driven by composite erosion.

Keywords: Soil Erosion; Water Quality Evolution; Coupling Mechanism; Land Use; Erosion Control Practices; Diffuse Pollution

1. Introduction

Soil erosion has long been recognized as a worldwide environmental challenge that not only causes land productivity degradation but also transports nitrogen, phosphorus, heavy metals, and other pollutants into water bodies via sediment transport, triggering water quality deterioration and eutrophication, thereby threatening aquatic ecosystem security in watersheds [1,2]. The Yellow River Basin ranks among China's most severely eroded regions, where the upper reaches characterized by coarse sediment and high sand content represent key and challenging areas for erosion control and water quality protection [3]. Originating from the hilly and gully region of the Loess Plateau in an arid and semi-arid zone, the Zuli River functions as a first-order tributary in the upper reaches of the Yellow River. Composite erosion features (hydraulic, wind, and freeze–thaw) are significant within the basin, and erosion-induced sediment production directly determines the sediment and pollutant fluxes entering the Yellow River. The erosion–water quality coupling relationship in this basin is typically representative of arid and semi-arid watersheds.

A complex feedback relationship exists between soil erosion and water quality evolution. On the one hand, sediment produced by erosion is the main carrier of pollutants, and erosion intensity directly determines the flux of pollutants entering rivers [4,5]. On the other hand, water quality changes such as eutrophication and sediment resuspension can reversely affect erosion and sediment transport processes [6]. Land use is the core link connecting human activities and natural processes, and regulates the erosion-water quality coupling relationship by changing surface cover, soil properties and hydrological processes [7,8]. Soil and water conservation measures have become an important means to synergistically achieve erosion control and water quality improvement by regulating hillslope runoff, intercepting sediment and purifying pollutants [9,10].

Following China's push for ecological conservation and high-quality development across the Yellow River Basin, research on watershed erosion–water quality coupling mechanisms has become increasingly important. However, existing studies have predominantly focused on single processes or single scales, and systematic research targeting arid and semi-arid loess hilly small watersheds remains relatively weak. Based on the fundamental theories of hillslope erosion dynamics, this paper systematically reviews the coupling mechanism between watershed soil erosion and water quality evolution, identifies research deficiencies and development directions by integrating the regional characteristics of the Zuli River Basin, and provides theoretical references for comprehensive watershed management.

2. Foundation of Hillslope Erosion Dynamics: Particle Detachment and Sediment Load Capacity.

Slope erosion and sediment production constitute important sources of non-point source pollution, with soil detachment and sediment transport being the core processes in erosion. The dynamics of these processes form the theoretical foundation for understanding the coupled relationship between erosion and water quality.

2.1 Hydrodynamic Mechanisms of Soil Detachment Process

Soil detachment is the initial stage of erosion, referring to the process by which soil particles are dislodged from the soil mass under the action of runoff. It is dually controlled by the external force of hydrodynamic erosion and the internal force of soil anti-erodibility [11,12]. Among hydrodynamic parameters, discharge and slope gradient are positively correlated with soil detachment rate, but the functional forms vary with experimental conditions, showing linear, power function and other forms [13,14]. The correlation between flow velocity and soil detachment is better than that of single parameters such as discharge and slope gradient, and it is a commonly used indicator for simulating detachment processes [15,16]. Comprehensive hydrodynamic parameters such as flow shear stress, stream power and unit stream power are widely used to simulate detachment processes. Most studies show that stream power has better explanatory ability for soil detachment, especially on steep yellow soil and loess slopes [17,18].

Soil intrinsic properties are key factors influencing erodibility: clay content, water-stable aggregates, and organic matter are all negatively correlated with soil detachability, while higher bulk density and greater soil compaction increase detachment difficulty [19–21]. Rill development significantly alters erosion processes: once rills form, flow becomes concentrated and erosion intensifies. The evolution of rill morphology is mutually feedback-related with hydrodynamic characteristics and erosion intensity, with rill erosion primarily driven by vertical and headward erosion, though bank collapse also plays a non-negligible role [22,23]; predicting soil detachment under high-flow concentrated flow conditions remains a current research focus [24].

2.2 Mechanisms Influencing Hillslope Runoff Sediment Transport Capacity

The sediment transport capacity of slope runoff is a key parameter determining the flux and form of sediment transport, and is comprehensively controlled by hydrodynamic conditions, underlying surface characteristics, and sediment properties [25,26]. Flow velocity is the core indicator characterizing the sediment transport capacity. The slope erosion amount has a significant power function relationship with the runoff velocity, and is a sensitive discriminant parameter for the erosion sediment yield intensity [27,28]. Slope gradient and discharge jointly determine the magnitude of erosion force: the influence of discharge on sediment transport capacity is generally stronger than that of slope gradient, but in steep slope gradient conditions, the contribution of slope gradient significantly increases, and the two are often in a power function relationship with the sediment transport capacity [29-30]. The discharge also has a regulatory effect. In turbulent and rapid flow conditions, the turbulence of the flow increases, and the ability of sediment initiation and transport is significantly enhanced [31,32].

The characteristics of sediment directly determine the efficiency of transport: the larger the sediment particle size, the higher the starting flow velocity and settling velocity, and the erosive force decreases according to a power function [33,34]. During the erosion process, sediment exhibits sorting characteristics. Fine particles are transported in suspended form, have a large specific surface area, and have strong adsorption capacity for pollutants, making them the main carriers for the migration of nutrients and pollutants; coarse particles mostly move in jump or push forms, with relatively weaker adsorption capacity [35-36]. This sorting characteristic is an important mechanism by which erosion affects the variation of water quality.

2.3 Feedback Mechanisms between Soil Detachment and Sediment Transport

Soil detachment and sediment transport are mutually restrictive. The sediment transport process has a feedback effect on detachment, and it is the core theoretical basis of the erosion process model [11,37]. When the sediment content in the runoff is lower than the sediment transport capacity, the flow continuously separates the soil using the remaining energy, and the sediment transport rate gradually increases; when the sediment content reaches the sediment transport capacity, detachment and transport reach a dynamic equilibrium, and the runoff is in a critical state of neither erosion nor deposition [38,39].

Under the erodible bed conditions, the silt carrying flow will reverse the water dynamic characteristics, thereby affecting the soil detachment ability. The coupling degree of the two directly determines erosion intensity and sediment particle size distribution, and ultimately affects the occurrence form and transport flux of pollutants [40,41]. Clarifying the detachment-transport feedback mechanism is a prerequisite for quantifying the relationship between erosion sediment yield and pollutant export.

3. Coupling Relationship Between Watershed Soil Erosion and Water Quality Evolution

3.1 Mechanism of Sediment-Nutrient Coupled Transport

Soil erosion acts as a major contributor to watershed non-point source pollution [4,5]. Under heavy rainfall conditions, hillslope erosion carries topsoil nutrients into river channels, and sediment, as the main carrier of pollutant migration, its adsorption-desorption process is the core pathway through which erosion affects water quality. Sediment has significant sorting characteristics during erosion: fine sediment particles have large specific surface area and many adsorption sites, with strong pollutant adsorption capacity, and the pollutant concentration carried is significantly higher than that of coarse particles; coarse particles mostly move in saltation and bedload, with relatively weak adsorption capacity [21,22]. Therefore, the higher the erosion intensity and the larger the proportion of fine particles, the more significant the increase in water pollutant concentration.

Research on loess plateau sloping cropland indicates that adsorbed nitrogen and phosphorus make up over 60% of all nutrients lost, and sediment transport represents the dominant pathway of nutrient loss [42]. During deposition, nutrients are redistributed with sediment, and different erosion intensity zones exhibit significant spatial variations in their contributions to downstream water quality [43]. In addition to directly increasing water turbidity and affecting aquatic ecosystems, erosion-induced sediment carries nutrients that trigger eutrophication risks and threaten drinking water safety [44–45]. During flood seasons, the Zuli River Basin transports substantial pollutants via high-sediment flows, representing an important influencing factor for fluctuations in stream chemistry along the Yellow River mainstream; however, the quantitative erosion–water quality response relationship within this basin remains unclear [3].

3.2 Multi-Scale Coupling Simulation

The erosion–water quality coupling process exhibits significant scale dependence: at the hillslope scale, soil detachment, transport, and deposition processes are directly controlled by hydrodynamic conditions and soil properties; at the small watershed scale, spatial heterogeneity in topography and land use drives spatial differentiation in erosion-induced sediment production and water quality response; at the watershed scale, climatic patterns and human activities jointly determine long-term evolution trends of erosion and water quality [46,47].

Researchers usually split current coupling simulation approaches into two camps. Physically based frameworks sit on one side, and empirical statistical models on the other. WEPP, SWAT, AnnAGNPS, and RUSLE are the typical examples they pull out. The WEPP model, based on water erosion physical processes, can provide detailed simulations of hillslope and watershed erosion-induced sediment production dynamics; however, its built-in nutrient module is functionally limited, capable only of simulating simple nitrogen loss, and its capacity to characterize water quality processes such as phosphorus and heavy metal adsorption–desorption and speciation transformation is relatively weak. The SWAT model integrates hydrological cycle, soil erosion, and nutrient cycling modules, with its erosion module employing the Modified Universal Soil Loss Equation (MUSLE), enabling simulation of runoff, sediment yield, and non-point source pollution loads under different land uses, and it has been widely applied in Loess Plateau watersheds; however, this model involves numerous parameters and complex calibration processes, and its default runoff generation module (SCS-CN) is adapted primarily to regions dominated by saturation-excess runoff. In small watersheds within arid and semi-arid zones dominated by Hortonian overland flow, the applicability of coupled simulation of runoff, sediment transport, and nutrients still requires localization, calibration, and validation [48]. RUSLE (The Revised Universal Soil Loss Equation), as a classic empirical statistical model, is widely applied in assessing regional soil erosion sensitivity and mapping spatiotemporal patterns of erosion modulus due to its accessible parameters and simple calculation [49]; however, this model can only output annual hillslope erosion amounts, cannot characterize rainfall-event-scale sediment transport processes, and is unable to represent the dynamic coupling mechanism between erosion and water quality. In recent years, the coupling of machine learning and physical models has provided a new approach to improving simulation accuracy, effectively optimizing parameter calibration efficiency and capturing nonlinear coupling relationships. However, there are common limitations such as weak explanatory power of physical mechanisms and insufficient extrapolation applicability [50].

In summary, the existing research has obvious shortcomings: a single model is unable to effectively integrate multi-scale processes of hillslope - small watershed - river basin, and the description of physical-chemical coupled processes such as sediment adsorption - desorption and nutrient form transformation is insufficient, resulting in difficulties in accurately quantifying the contribution ratio and driving mechanism of soil erosion to water quality [51]. The existing research in the Zulihui River Basin mainly focuses on the spatiotemporal evolution characteristics and influencing factors of soil erosion, and lacks coupled simulation research on erosion-driven non-point source pollution, making it difficult to meet the precise management requirements of river water quality.

4. Regulatory Mechanisms of Land Use in the Erosion–Water Quality Relationship

4.1 Dual Regulatory Effects of Land Use on Soil Erosion and Water Quality

Land use types affect soil erosion intensity and water quality simultaneously by altering surface cover, soil structure, and hydrological pathways. They are important regulatory factors in the erosion-water quality coupled system [7,8]. In terms of erosion regulation, the soil detachment capacity under different land use types in the Loess Plateau generally follows the pattern of farmland > grassland > shrubland > forestland: Farmland, due to long-term cultivation disturbance, damages the soil aggregate structure, making the surface soil loose, and significantly increasing soil erodibility and detachment capacity, resulting in the highest erosion risk; Forestland and grassland achieve erosion reduction effects through multiple mechanisms such as canopy interception of rainfall, root fixation of soil, and sediment reduction by litter, and as the duration of reforestation and regrassing increases, soil organic matter and aggregate stability gradually improve, showing a non-linear enhancement trend in soil erosion resistance [52-54]. The amplification effect of farming activities on erosion is significant. The soil detachment capacity under the traditional tillage pattern can reach about 10 times that of no-tillage pattern; Equal-height tillage, stubble cover, and other protective tillage patterns can effectively reduce slope erosion risk by improving soil structure and weakening runoff erosion [55,56].

In terms of water quality impact, different land uses regulate water quality through the dual paths of pollution source input and hydrological process: Urban construction land expands impermeable surfaces, shortens runoff time, and enhances runoff erosion capacity, significantly increasing the pollution flux and peak concentration of suspended solids, organic matter, and heavy metals in runoff; Agricultural farmland, due to external input of fertilizers and pesticides, is not only an important source of dissolved nitrogen and phosphorus, but also increases the output load of particulate nutrients through soil erosion, being the core contributor to non-point source nitrogen and phosphorus pollution; Forestland and grassland, through multiple functions such as retaining runoff, filtering sediment, plant absorption and soil adsorption, simultaneously reduce particulate and dissolved pollutants, exerting significant water quality purification functions [57,58]. From a temporal perspective, during the rainy season with abundant rainfall and runoff, slope erosion and sediment production are active, and non-point source pollution dominates, with water quality mainly regulated by the spatial layout of land use; During the dry season with small runoff volume and weak dilution capacity, the contribution of point source pollution increases, and water quality is jointly affected by the background of land use and hydrological conditions, as well as point source emissions [59]. The riverbank area, as a key corridor at the interface of land and water, its vegetation destruction directly weakens the sediment interception and pollutant reduction functions, being an important cause of water quality deterioration in the watershed [60].

4.2 Land Use Optimization and Buffer Zone Regulation Strategies

Optimizing the land use structure is a macroscopic fundamental means for jointly controlling soil erosion and water pollution. By increasing the area of forests and grasslands to reduce erosion sources, optimizing the landscape pattern to block the migration paths of pollutants, and enhancing landscape connectivity to strengthen the overall regulatory capacity of the ecosystem, the erosion index and pollutant output load can be simultaneously reduced. Studies have shown that targeted land use optimization can reduce nitrogen and phosphorus output by 30% to 50% [61,62]. Based on the optimization of land use structure, the riparian buffer is the key ecological interface connecting the land and water areas. It purifies runoff through multiple mechanisms such as physical sediment interception, plant absorption, soil pollutant adsorption, and microbial degradation. Among them, the composite buffer zone of trees, shrubs, and grasses has the best purification effect, with a sediment interception efficiency of up to 60% to 90%, and the removal rates of nitrogen and phosphorus are 20% to 80% and 30% to 90%, respectively [63,64]. In arid and semi-arid regions, considering water resource constraints and management costs, the herbaceous buffer zone is a more valuable alternative choice due to its strong drought resistance and low maintenance costs.

5. Erosion Control Mechanisms and Water Quality Improvement Mechanisms of Soil and Water Conservation Measures

5.1 Erosion Mitigation Effects of Soil and Water Conservation Measures

According to the mechanism of action and implementation methods, soil and water conservation measures can be classified into three major categories: engineering measures, plant measures, and agricultural cultivation measures. These measures work together to reduce erosion and sediment production through regulating erosion dynamic processes, improving the underlying surface conditions, or intercepting sediment transport [9,10]. Plant measures are the fundamental biological means for erosion control. Through multiple mechanisms such as canopy interception to reduce rainfall kinetic energy, root system fixation to enhance soil erosion resistance, and litter cover to protect the surface, vegetation significantly reduces the rate of soil detachment and runoff erosivity. The implementation results of the reforestation and grass planting project in the Loess Plateau show that the soil erosion modulus in the vegetation restoration areas is reduced by more than 60% compared to agricultural farmland [65,66]. Engineering measures are the key structural means for erosion control, achieving control through changing terrain conditions and regulating hydrological processes: terraces shorten slope lengths and slow mean flow velocities to inhibit the formation and headward expansion of rills;

Silt storage dams, sedimentation basins, etc. reduce the amount of sediment entering rivers by directly intercepting sediment. Studies have shown that the sediment transport capacity of erosive runoff is approximately 2.9 times that of non-erosive runoff, so the transformation of erosive runoff to non-erosive runoff through runoff regulation is the core theoretical basis for engineering erosion control [67]. Agricultural cultivation measures are important auxiliary means for erosion control, improving soil structure, promoting aggregate formation, and regulating the development of surface crusts to enhance soil erosion resistance. Protective tillage, contour planting, and straw covering measures can effectively reduce the separation ability of slope runoff and sediment transport flux [68,69]. A large number of silt storage dams have been built in the Zulih River Basin, and the sand interception and erosion reduction benefits are significant, but the synergistic improvement effect on water quality has not been systematically evaluated.

5.2 Water Quality Improvement Mechanism and Synergistic Optimization Configuration

Soil and water conservation measures not only play a role in reducing erosion, but also, through the triple mechanisms of "physical filtration and deposition - biological absorption and transformation - ecological buffering and self-purification", jointly improve water quality and achieve the coupled benefits of erosion control and water quality enhancement. Riparian buffer zones, terraced fields, and sedimentation basins reduce surface runoff velocity and prolong hydraulic residence time, enabling gravity-driven deposition of sediment particles and their attached adsorbed pollutant loads. Water turbidity drops and particulate pollutant concentrations fall [63,70].

Biological absorption and transformation run in parallel. Plant roots directly absorb nitrogen, phosphorus, and other nutrients. Soil microorganisms convert nitrogen into gaseous nitrogen through nitrification–denitrification processes. This strips pollutants from the soil-water system [71,72].

Ecological buffering and self-purification mechanism: ecological ditches, constructed wetlands, and riparian vegetation restoration enhance the natural purification capacity of ecosystems, extend contact time between pollutants and biofilms, and promote microbial degradation of organic pollutants and nutrient transformation and cycling [73,74]. Ecosystem service assessment tools such as the InVEST model have been widely applied for quantitative assessment of erosion control alongside stream chemistry regulation functions [73,74].

Synergistic allocation of multiple measures can generate cumulative effects of "erosion reduction–sediment interception–pollutant purification": combinations of terraces with forest and grass measures can reduce erosion modulus by more than 80% while significantly reducing nitrogen and phosphorus output loads [75]; cascade allocation of ecological measures such as buffer zones and constructed wetlands can achieve stepwise removal of different pollutant forms, enhancing overall purification efficiency [76].

However, current soil and water conservation research still exhibits a tendency of "emphasizing erosion reduction while neglecting water quality": research on the water quality effects of engineering measures and agricultural tillage measures remains weak, and a quantitative assessment system for collaborative optimization of multiple measures has not yet been established, limiting the optimization of measure allocation oriented toward water quality improvement [77].

6. Research Deficiencies and Prospects

6.1 Existing Research Deficiencies

Considering the regional characteristics of the Zuli River Basin—arid and semi-arid climate, intense composite erosion, and ecological fragility—the following deficiencies remain in current erosion–water quality coupling research:

(1) Unclear multi-scale coupling mechanisms. Existing research predominantly focuses on single scales such as hillslope, small watershed, or watershed; the erosion–water quality transformation relationships and scale effects among hillslope–small watershed–watershed multi-scales have not been systematically elucidated. Single models struggle to effectively integrate multi-process coupling of hydrology–erosion–nutrients, making it difficult to quantitatively distinguish the relative contribution of erosion to water quality, thereby limiting the prediction accuracy of watershed-scale erosion–water quality responses.

(2) Absence of water quality effectiveness assessment systems for measures. Soil and

water conservation research has long focused on erosion reduction as the primary evaluation metric, with insufficient attention to the ecosystem service functions of water quality improvement. Water quality effects of structural interventions (such as check dams and terraces) and agricultural measures (such as conservation tillage) lack support from long-term in-situ observation data, and research on collaborative optimization allocation of multiple measures oriented toward water quality improvement goals remains underdeveloped.

(3) Inconsistent experimental methods and standards. Measurement methods and experimental standards for key parameters such as soil detachment capability and runoff sediment carrying capacity have not yet been unified, resulting in poor comparability among different research results, making model parameters difficult to regionalize, transfer, and verify, and affecting the reliability and generality of erosion–water quality coupling simulation.

6.2 Future Research Prospects

To address the above deficiencies, future work should focus on the following:

(1) Construct multi-scale coupling simulation methodological frameworks. Integrate field long-term in-situ monitoring, UAV remote sensing aerial survey, and multi-process coupling model simulation to establish quantitative relationships for hillslope–small watershed–watershed multi-scale erosion–water quality transformation; develop hydrology–erosion–nutrient coupling simulation models applicable to arid and semi-arid small watersheds, achieving quantitative partitioning of erosion contribution to water quality and precise prediction of watershed-scale responses.

(2) Establish water quality effectiveness assessment systems for soil and water conservation measures. Systematically conduct long-term in-situ observations of the synergistic erosion reduction–water purification effects of typical measures including vegetation restoration, terraces, check dams, and conservation tillage; reveal the synergistic mechanisms and threshold effects of the multiple functions of "erosion reduction–sediment interception–pollutant purification"; construct spatial optimization models for multiple measures oriented toward water quality improvement goals, providing quantitative decision support for comprehensive watershed management planning.

(3) Unify key parameter experimental standards and methodological norms. Develop standardized measurement protocols for core parameters such as soil detachability and sediment-carrying capacity of runoff, standardizing experimental conditions and measurement methods; establish regionalized model parameter databases to enhance comparability among different research results and regional transferability of model parameters, ensuring the reliability and generality of erosion–water quality coupling simulation.

7. Conclusions

This paper systematically reviews research progress on the coupling mechanism between watershed soil erosion and water quality evolution from five dimensions: hillslope erosion dynamics, sediment–nutrient co-transport, multi-scale coupling simulation, land use regulation, and soil and water conservation measure effects. The main findings are summarized below:

(1) The dynamic process of soil detachment–sediment transport constitutes the physical foundation of the erosion–water quality coupling relationship. Soil detachment, as the initial stage of erosion, is governed by both hydrodynamic conditions and soil resistance to erosion properties; runoff sediment transport capacity determines sediment transport flux and morphological sorting, thereby influencing pollutant occurrence forms and transport fluxes; the detachment–transport feedback mechanism is a prerequisite for quantifying the relationship between erosion-induced sediment production and pollutant export.

(2) Sediment is the primary carrier for pollutant migration. The way particles sort by size and their transport behavior then governs how intensely water quality responds. Fine sediment particles, due to their large specific surface areas and strong adsorption capacity, become the primary carriers of nutrient and pollutant migration; the erosion–water quality coupling process exhibits significant scale dependence, and the multi-scale transformation relationships and coupling mechanisms among hillslope–small watershed–watershed remain key gaps in current research.

(3) Land use simultaneously regulates soil erosion and water quality processes by altering

erosion dynamics and pollutant sources. Land use structure optimization can reduce erosion-induced sediment production and pollution loads from the source; riparian buffer zone construction achieves runoff purification through multiple mechanisms of physical interception, biological absorption, and ecological self-purification, representing effective pathways for synergistic erosion control and water purification.

(4) Soil and water conservation measures simultaneously achieve erosion control and water quality improvement through multiple effects of "erosion reduction–sediment interception–pollutant purification." Vegetation measures, engineering measures, and agricultural tillage measures each possess advantages in erosion reduction functions; however, current research exhibits a tendency of "emphasizing erosion reduction while neglecting water quality," with research on the water quality effects of engineering measures and agricultural measures and collaborative optimization allocation of multiple measures remaining underdeveloped.

(5) Future research should focus on composite erosion characteristics in arid and semi-arid watersheds, with priority breakthroughs in three directions: multi-scale coupling simulation, water quality effect assessment of measures, and standardization of key parameters. Construct hydrology–erosion–nutrient coupling models applicable to arid and semi-arid small watersheds; establish soil and water conservation measure optimization allocation systems oriented toward water quality improvement goals; and underpin ecological conservation and sustainable growth in the Zuli River Basin and similar regions.

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