

Research on Landscape Regulation Design for Water Pollution in Decommissioned Uranium Tailings Ponds Based on Nature-based Solutions

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Abstract:

Driven by rainfall runoff, decommissioned uranium tailings ponds are prone to generate surface wastewater containing pollutants that diffuses to surrounding areas along the terrain, posing potential risks to the ecological environment and residents' safety in downstream rural regions. Existing treatment methods mostly rely on engineering measures such as interception and drainage, as well as chemical treatment, with a primary focus on end-of-pipe pollution control, while insufficient attention is paid to the pollution migration process and the regulatory function of landscape space. Taking a decommissioned uranium tailings pond and its downstream rural catchment area as a case study, this study analyzes the spatial distribution characteristics of surface runoff and pollution migration paths by integrating topographic, hydrological and land use data, identifies key landscape nodes and ecological buffer units, and discusses the action mechanisms of different landscape elements in the processes of pollution interception, retention and purification. On this basis, a natural process-oriented multi-level landscape regulation strategy is proposed, including source reduction, process regulation and end purification. The research results can provide references for landscape planning and design in terms of mining area water pollution control and ecological security of downstream rural areas.

Keywords:

Decommissioned Uranium Tailings Ponds, Nature-based Solutions, Landscape Regulation, Pollutant Migration

1. Introduction

The exploitation of uranium ore resources has boosted the development of the nuclear energy industry, while also resulting in significant tailings storage challenges. Under the long-term influence of rainfall and surface runoff, some decommissioned uranium tailings ponds are likely to form surface wastewater containing pollutants that spreads to adjacent areas along the terrain, exerting potential impacts on the ecological environment and residents' daily lives in downstream rural areas. Therefore, how to effectively control pollution migration and reduce environmental risks during the ecological restoration of mining areas has gradually become a crucial issue in

mining area environmental governance. Existing studies are mostly conducted from an engineering technology perspective, controlling pollutant discharge through measures such as tailwater interception, chemical precipitation and anti-seepage treatment. Such methods achieve certain effects in short-term pollution control, yet they often focus on end treatment and neglect the migration paths of pollutants in landscape space as well as the regulatory role of ecosystems. In recent years, Nature-based Solutions (NbS) have gained extensive attention in the fields of water environment governance and ecological restoration, the core of which lies in utilizing the self-regulating capacity of ecosystems to realize the overall improvement of environmental resilience [1]. Ecological elements including wetland systems, vegetation buffer zones and topographic regulation can play a synergistic role in pollution interception, retention and purification, thus providing new ideas for water environment governance in mining areas. Based on this, this paper takes a decommissioned uranium tailings pond and its downstream catchment area as the research subject, analyzes the pollution migration process from the perspective of landscape space, identifies key landscape nodes, and puts forward corresponding landscape regulation strategies.

2. Significance of Landscape Regulation for Water Pollution in Decommissioned Uranium Tailings Ponds

The water pollution issue of decommissioned uranium tailings ponds has long threatened the ecological and human settlement safety of downstream rural areas, making it imperative to propose systematic governance methods from spatial and ecological perspectives. This paper combines Nature-based Solutions with landscape design, explores the spatial regulation mechanism of the pollution migration process, and advances a multi-level landscape intervention strategy. This research not only enriches the theoretical framework of water environment governance in mining areas, but also provides an operable design path for the ecological restoration of decommissioned mining areas, as well as a new methodological reference for the protection of rural environmental safety and the sustainable management of industrial brownfields.

3. Current Challenges in Water Pollution Governance of Decommissioned Uranium Tailings Ponds

3.1. Over-reliance on end-of-pipe engineering in traditional governance methods

Current water pollution governance of decommissioned uranium tailings ponds is mainly based on end-of-pipe treatments such as tailwater interception and chemical purification, with the focus on the final removal of pollutants, while systematic research on pollution sources, migration paths and spatial diffusion characteristics is lacking. This makes it difficult for governance measures to intervene in the entire pollution process; in particular, under the action of rainfall and surface runoff, pollutants tend to diffuse downstream along the terrain [2]. In addition, a single engineering approach cannot make full use of natural ecological processes, leading to high governance costs and insufficient sustainability.

3.2. Underutilization of landscape ecological functions

The role of mining area landscape units in pollution regulation and ecological restoration has not been fully explored. Ecological landscape elements such as

vegetation buffer zones, constructed wetlands and submerged plant areas have not been systematically integrated in terms of their functions of pollution interception, retention, purification and hydrological regulation. The lack of spatial function optimization leads to the disconnection between ecology and pollution governance, failing to achieve the synergistic effect of pollution control and ecological restoration, and also limiting the realization of the potential ecological service value of mining area landscapes.

3.3. Insufficient integration of spatial information and identification of key nodes

Topographic, hydrological and land use information are mostly analyzed in isolation in existing studies, lacking the support of comprehensive spatial analysis and key node identification methods. This makes it difficult to accurately grasp the laws of pollution migration and to provide a scientific basis for landscape intervention. Without the guidance of spatial strategies, governance measures are often unable to accurately match high-risk areas, thus reducing the efficiency of resource utilization and the effect of ecological intervention.

3.4. Lack of integrity in environmental risk prevention and control in downstream rural areas

Farmland, water bodies and residential areas in the downstream of decommissioned mining areas are facing potential pollution threats, yet existing governance studies mostly focus on technical treatment while ignoring the comprehensive consideration of rural ecological security and social needs. The lack of systematic evaluation and multi-level prevention and control strategies renders protective measures scattered and unsustainable, failing to form a full-process protection system from pollution sources to receptors, and thus reducing the long-term effect and social acceptability of governance.

3.5. Limited application of Nature-based Solutions in mining area governance

Although Nature-based Solutions have received widespread attention in water environment governance and ecological restoration, their practical cases in decommissioned uranium tailings ponds are still scarce, with a lack of operable landscape design methods and strategy systems [3]. Existing studies mostly remain at the level of theoretical discussion or single technology, making it difficult to provide specific design guidance or implementation standards.

4. Landscape Regulation Strategies Based on Nature-based Solutions

4.1. Source Reduction Strategy

In the uranium tailings pond and its surrounding areas, the formation of surface runoff and pollutant loss are controlled through topographic transformation, rainwater guidance and surface coverage measures. Permeable pavement, surface vegetation coverage, rainwater collection and slow-release facilities are adopted to achieve the initial interception of rainfall runoff and the reduction of pollution load. Meanwhile, combined with slope regulation and the layout of intercepting ditches, rainwater is guided to flow along low-risk paths, reducing the migration of pollutants to the downstream from the source and laying a solid foundation for the entire landscape regulation system.

4.2. Process Regulation Strategy

Multi-layer ecological buffer units are established along pollution migration channels, including constructed wetlands, buffer zone vegetation, submerged plant areas and ecological ditches. Through various action mechanisms such as physical sedimentation, plant absorption and microbial degradation, the runoff speed is slowed down and the pollutant concentration is reduced [4]. At the same time, combined with terrain slope, hydrological distribution and land use types, the runoff path is optimized to realize the coordination of pollution control and ecological functions.

4.3. End Purification Strategy

Wetland purification ponds, sand settling areas and ecological filter beds are constructed in downstream rural areas and key water body regions to realize the advanced treatment of residual pollutants. The end design focuses on integration with rural landscape space, and balances functional needs and landscape aesthetics through wetland landscapes, ornamental water bodies and ecological trails, which not only improves water quality but also optimizes the leisure environment of villagers. Additionally, ecological indicator species can be used to monitor changes in water quality, and vegetation restoration technology can be adopted to enhance environmental resilience [5].

4.4. Spatial Node Optimization Strategy

Based on the simulation analysis of topography, hydrology, land use and rainfall runoff, the key nodes and high-risk areas of pollution migration are identified. Wetlands, vegetation buffer zones, sand settling facilities and ecological ditches are arranged in a targeted manner at these nodes to realize the early interception and multi-level regulation of pollutants in space. Spatial diagnosis of damaged sites through landscape ecology models can significantly improve the efficiency of ecological intervention.

4.5. Multi-level Synergy Strategy

Source reduction, process regulation and end purification are integrated into a continuous multi-level landscape governance system, forming a closed-loop mechanism of pollution prevention and control - ecological buffer - purification and restoration. Through the synergistic effect of Nature-based Solutions and landscape design, the comprehensive goals of pollution control, ecological restoration and landscape optimization are achieved. This strategy can adapt to different rainfall conditions and topographic environments, taking into account mining area safety, downstream rural ecology and landscape aesthetics, and thus providing a systematic and sustainable implementation path for water pollution governance in decommissioned mining areas.

5. Conclusions

Water pollution in decommissioned uranium tailings ponds features long-term persistence and spatial diffusion, posing potential threats to the ecology and residents' safety in downstream rural areas. This paper introduces Nature-based Solutions from the perspective of landscape design, and proposes a multi-level landscape strategy with source reduction, process regulation, end purification and key spatial node optimization as the core. By constructing ecological buffer units, optimizing runoff

paths and integrating landscape functions, pollution migration can be effectively intervened, and the coordination of pollution control and ecological restoration can be realized. The research shows that landscape intervention not only improves the environmental safety and ecological resilience of downstream areas, but also provides an operable design method for the ecological restoration of decommissioned mining areas, as well as practical references for the management of industrial brownfields and the optimization of rural environments. In the future, the effect of the proposed strategy can be further verified and improved by combining field tests and long-term monitoring.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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