

Research and Application of Groundwater Pollution Remediation Technologies

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ABSTRACT

This paper focuses on key technologies, innovative approaches, and practical applications in the field of groundwater pollution remediation. It begins by examining the current state of groundwater contamination, identifying various pollution sources and their significant impacts on the environment and society. The discussion then categorizes physical, chemical, and biological remediation methods, with particular emphasis on innovative directions such as the use of advanced materials, integrated multi-technology strategies, and techno-economic assessments. Finally, case studies are presented to illustrate the effectiveness of multi-technology approaches in addressing complex polluted sites.

KEYWORDS

groundwater; pollution remediation; technology research; technology application

1 Introduction

As one of the most critical freshwater resources on Earth, groundwater plays an indispensable role in maintaining ecological balance and meeting human needs for production and daily life. However, with the accelerating pace of industrialization and urbanization, groundwater is facing unprecedented pollution challenges. Contaminants from industrial wastewater, agricultural fertilizers and pesticide residues, and domestic sewage seep into aquifers through various pathways, leading to a deterioration in groundwater quality. This not only reduces the efficient utilization of water resources but also causes severe damage to the ecological environment. In light of this pressing issue, researching and implementing effective groundwater pollution remediation technologies has become increasingly urgent.

2 Analysis of Groundwater Pollution Status

2.1 Identification of Pollution Sources

Groundwater pollution arises from a variety of sources, spanning industrial, agricultural, and domestic activities. Among these, industrial wastewater discharge is one of the most significant contributors. During chemical production processes, wastewater containing heavy metals and organic compounds is often inadequately treated before being released into the environment. These pollutants infiltrate aquifers through soil, resulting in the deterioration of groundwater quality^[1]. Similarly, oil extraction activities can cause severe groundwater contamination through leakage incidents, where harmful substances like benzene compounds lead to persistent and widespread pollution.

Agricultural practices, particularly the use of fertilizers and pesticides, are another major source of contamination. With the advancement of modern agriculture, the application of these chemicals has steadily increased over the years. Rainwater runoff and irrigation can transport these substances into groundwater, causing excessive levels of nitrates, phosphates, and pesticide residues. In regions where nitrogen fertilizers are overused, nitrate concentrations in groundwater often exceed national safety standards, posing a direct threat to the drinking water safety of local communities.

Domestic wastewater also plays a significant role in groundwater contamination. During urbanization, wastewater treatment infrastructure often fails to cover all areas, resulting in untreated sewage being discharged directly into natural water bodies or seeping into the ground. This introduces large quantities of pathogenic microorganisms and nutrients, which severely impact groundwater quality. The issue is particularly acute in older urban areas, where aging and damaged drainage systems exacerbate the problem.

2.2 Pollution Characteristics and Impacts

Groundwater pollution is characterized by its concealed and delayed nature, making it difficult to detect until it has caused extensive damage. For instance, in the eastern industrial zone of Oakland, California, long-term discharge of heavy metal wastewater from nearby factories resulted in groundwater contamination with lead and mercury levels far exceeding safety standards. This not only damaged the local ecological environment but also posed potential risks to

human health through bioaccumulation in the food chain.

From an environmental perspective, groundwater pollution disrupts the balance of ecosystems. For example, certain pesticide residues entering groundwater can interfere with the metabolism of aquatic organisms, potentially leading to species extinction. Additionally, since groundwater is a crucial source of recharge for rivers, lakes, and other surface water bodies, its contamination directly impacts surface water quality, triggering a cascade of adverse effects on the entire watershed ecosystem. On a societal level, groundwater contamination directly affects human survival and development. The safety of drinking water is a key indicator of living standards in any region. When groundwater is polluted, residents are often forced to rely on expensive bottled water or long-distance water transfers to meet daily needs, significantly increasing their living costs^[2]. Furthermore, groundwater pollution can lead to public health crises, such as outbreaks of diarrhea, parasitic infections, and other diseases, placing an additional burden on society.

3 Classification of Groundwater Pollution Remediation Technologies

3.1 Physical Remediation Methods

Physical remediation techniques utilize physical processes to remove or isolate contaminants in groundwater, aiming to purify water quality. Pump-and-treat is a widely adopted physical remediation approach that involves extracting contaminated groundwater to the surface for treatment before either reinjecting it into the aquifer or discharging it. This method is effective for organic pollutants and certain heavy metals, but its implementation requires careful consideration of groundwater flow characteristics and pollutant distribution to prevent secondary contamination. Air sparging, on the other hand, employs mass transfer between gas and liquid phases to volatilize organic compounds dissolved in water into the air. This technique works well for removing volatile organic compounds such as benzene, though its effectiveness is constrained by soil permeability and operational costs. Lastly, thermal desorption involves heating contaminated soil to volatilize adsorbed organic pollutants, which are then collected and treated via a gas treatment system. This method is particularly advantageous for high-concentration, recalcitrant organic pollutants but faces challenges such as high energy consumption and the risk of secondary pollution during operation.

3.2 Chemical Remediation Methods

Chemical remediation techniques rely on chemical reactions to transform or immobilize contaminants in groundwater, thereby reducing their toxicity or mobility. Among these, chemical oxidation-reduction is a crucial approach that introduces strong oxidants like persulfates or Fenton's reagent into groundwater to degrade organic pollutants into carbon dioxide and water. For example, Fenton oxidation has proven effective in breaking down polychlorinated biphenyls (PCBs), achieving rapid degradation by disrupting the molecular structure of contaminants. However, the method is limited by issues such as poor selectivity of reagents and the potential formation of by-products, which can restrict its application in specific environments. Precipitation, another common chemical method, involves the reaction of chemical precipitants with contaminants to form insoluble precipitates that can be separated from the water^[3]. This technique is particularly suitable for treating groundwater contaminated with heavy metal ions, such as using limestone to remove iron and manganese ions from acidic mine drainage. While simple and practical, precipitation faces challenges in ensuring long-term stability and adapting to complex pollutant compositions, as a single chemical precipitant often struggles to address the coexistence of multiple contaminants effectively.

3.3 Biological Remediation Methods

Biological remediation methods leverage the metabolic processes of microorganisms, plants, or their byproducts to degrade or transform contaminants in groundwater. Microbial degradation is one of the most commonly used approaches, where specific microbial communities are selected and enhanced to efficiently break down organic pollutants in subsurface environments. For instance, in petroleum hydrocarbon-contaminated sites, introducing hydrocarbon-degrading microbial strains can accelerate the natural attenuation process. However, the effectiveness of microbial degradation is influenced by environmental conditions such as temperature and pH, making the optimization of these parameters key to improving remediation efficiency.

Phytoremediation, a green and ecological restoration technique, has gained widespread attention in recent years. This approach involves cultivating hyperaccumulator plants to absorb, concentrate, and transfer heavy metals or other harmful substances from soil and groundwater, simultaneously improving water quality and the surrounding ecosystem. For example, Indian mustard has been shown to exhibit strong tolerance and uptake capacity for cadmium, making it a viable option for remediating cadmium-contaminated areas. Despite its environmental benefits, phytoremediation is limited by its lengthy remediation cycles and reduced effectiveness in highly contaminated regions, often necessitating

its integration with other remediation technologies to achieve optimal results.

4 Innovations in Groundwater Pollution Remediation Technologies

4.1 Application of New Materials

Advancements in science and technology have significantly expanded the application of new materials in groundwater remediation. Nanomaterials, such as nanoscale zero-valent iron (nZVI), exhibit high reactivity and exceptional adsorption capabilities, making them highly effective in addressing chlorinated organic compounds and heavy metal pollution. In industrial settings, injecting nZVI particles can reduce trichloroethylene concentrations in groundwater by over 95%. Additionally, nZVI demonstrates excellent removal efficiency for heavy metal ions like arsenic and chromium, offering novel solutions for complex contamination scenarios. However, challenges remain, particularly regarding the stability of nanomaterials, as they tend to aggregate and lose activity in natural environments. This has necessitated the development of stable carriers or surface modification techniques to enhance their durability and performance.

Apart from nanomaterials, the emergence of smart adsorbents has brought new hope to groundwater pollution management. Modified activated carbon and biochar are two commonly used smart adsorbents, whose chemical modification or incorporation of functional groups enhances their selectivity and adsorption efficiency for target contaminants. For example, ammonia-treated activated carbon has been shown to significantly improve nitrate adsorption capacity, making it suitable for purifying groundwater in agricultural regions. Biochar, with its abundant functional group structures, can form stable complexes with various organic pollutants, ensuring efficient removal. These new adsorbents not only exhibit favorable physicochemical properties but are also cost-effective and scalable for mass production.

4.2 Integrated Use of Multiple Technologies

Given the complexity of groundwater pollution, a single remediation technique often falls short of addressing all contaminants, making the integration of multiple methods an effective solution. By combining the strengths of physical, chemical, and biological approaches, researchers can design comprehensive remediation strategies tailored to specific contaminants. For instance, in cases of mixed pollution involving volatile organic compounds (VOCs) and heavy metals, volatile components can first be removed through air sparging. The remaining recalcitrant organic pollutants can then be treated with chemical oxidation-reduction techniques. Finally, a combination of microbial enhancement and phytoremediation can be applied, where hyperaccumulator plants are used to absorb heavy metal ions from the soil. This integrated approach not only improves remediation efficiency but also shortens treatment time and reduces overall costs.

In practical applications, the success of multi-technology integration depends on factors such as site conditions and pollutant characteristics. For example, at a chemical plant site affected by wastewater leakage, groundwater was simultaneously contaminated with benzene compounds and heavy metals. Initially, relying solely on chemical oxidation failed to eliminate all pollutants. The subsequent inclusion of phytoremediation, using resilient willow species, effectively reduced cadmium levels in both soil and water. Moreover, the site explored a microbe-plant combined remediation strategy by inoculating specific degradative microbial strains in the rhizosphere, accelerating the breakdown of organic pollutants^[4]. These coordinated measures ultimately achieved effective restoration of the contaminated area.

4.3 Techno-Economic Evaluation

For any emerging technology, assessing its scientific effectiveness alone is insufficient; a comprehensive techno-economic evaluation is essential to ensure feasibility and market potential. While nanomaterials and advanced oxidation technologies theoretically achieve high remediation efficiencies, their widespread adoption is often hindered by the high costs of research and implementation. In contrast, traditional modified adsorbents or nature-based methods, such as wetland restoration and vegetative buffer zones, are more appealing due to their lower costs and ecological benefits.

Support from government policies and private sector investment also plays a crucial role. To drive industry progress, governments should establish subsidies and tax incentives to encourage companies to invest in environmental technology research.

For instance, some EU member states have created dedicated funds to support groundwater remediation projects and reward businesses that adopt innovative technologies. As public awareness of environmental protection grows, market demand is increasingly shifting toward green and sustainable solutions, providing a vast application space for innovative remediation technologies. Nature-based solutions, such as wetland restoration projects, have gained traction not only for their ability to improve water quality but also for offering additional ecological services, such as climate regulation and

biodiversity conservation, positioning them as a focal point for future development.

5 Case Studies

5.1 Case Analysis

This chapter examines a typical remediation project addressing groundwater contamination caused by wastewater leakage from a chemical plant. Located in an industrial area in eastern China, the plant had long discharged wastewater containing substantial amounts of organic pollutants and heavy metals, resulting in severe groundwater degradation in the surrounding area. To tackle this issue, the project team implemented a multi-technology remediation strategy that combined chemical oxidation, bioremediation, and phytoremediation methods.

In the initial stage, the team employed persulfate oxidation to treat the high concentrations of benzene compounds in the groundwater. By injecting a persulfate solution into the contaminated zone, the strong oxidizing properties of the reagent were utilized to break down organic pollutants into harmless small-molecule substances. This step significantly reduced benzene compound concentrations but did not eliminate all contaminants. Consequently, the team adopted microbial enhancement techniques during subsequent treatment phases, introducing efficient degradative bacterial strains to accelerate the natural attenuation of residual organic pollutants. At the same time, willow trees and other hyperaccumulator plants were cultivated to absorb heavy metal ions, such as cadmium and chromium, from the soil, effectively mitigating heavy metal pollution.

To prevent further spread of contaminants, physical barriers were installed around the pollution source. Impermeable materials were used to construct containment zones, blocking pollutants from migrating to broader areas. The entire remediation project spanned three years, during which groundwater quality was regularly monitored, and the treatment plan was adjusted based on actual conditions.

5.2 Performance Evaluation

To comprehensively evaluate the outcomes of the remediation project, the team developed a scientific performance assessment framework. Several key indicators were identified to measure the effectiveness of the restoration, including concentrations of primary pollutants, ecosystem health, and the safety of local drinking water supplies. Comparative analyses of groundwater samples taken before and after the remediation revealed a significant reduction in benzene compound concentrations, meeting national drinking water standards. Heavy metal concentrations in the soil also decreased substantially, demonstrating the effectiveness of the bioremediation measures.

In terms of ecosystem health, vegetation coverage increased markedly, and biodiversity showed signs of recovery. The area where willows were planted evolved into a robust ecological barrier, which not only absorbed heavy metals from the soil but also improved the local microclimate. With improved groundwater quality, the safety of drinking water for local residents was ensured, reducing health risks associated with consuming contaminated water. From an economic perspective, although the initial investment in materials, equipment installation, and personnel training was significant, the long-term environmental and social benefits were substantial. For instance, reduced healthcare costs and increased land values indirectly generated economic gains. More importantly, the successful implementation of this project offered valuable experience and technical insights for the remediation of similar contaminated sites, driving advancements in groundwater pollution remediation technologies.

Nevertheless, certain challenges remain. For example, optimizing the integration of multiple technologies to enhance efficiency while reducing costs remains a key area for improvement. Additionally, strengthening post-remediation maintenance and management is critical to ensuring the sustainability of the results. These challenges highlight the need for future research to focus on combining technological innovation with practical applications, exploring more effective solutions to address complex pollution scenarios.

6 Conclusion

This article delves into the current state, classification, and innovative advancements of groundwater remediation technologies. Through detailed case studies, it highlights the potential of multi-technology integration in addressing complex pollution challenges. The discussion underscores the critical role of combining scientific knowledge with technological innovation to enhance remediation efficiency. It also emphasizes that the application of new materials and comprehensive remediation strategies offers renewed hope for groundwater pollution control. Future research should focus on developing more efficient, low-cost, and environmentally friendly remediation methods. Strengthening interdisciplinary collaboration and fostering technological innovation will be key to tackling the pressing global issue of

groundwater contamination. These efforts must be aligned with the sustainable management and protection of water resources.

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