Geochemical Responses and Environmental Feasibility of Managed Aquifer Recharge with Mine Water in Coal Mining Areas

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Abstract

The coal-water mismatch in China induces severe groundwater depletion in arid mining regions. This study proposes Mine Water Managed Aquifer Recharge (MMAR), a source-treatment-storage framework that returns treated mine water to aquifers for near-zero discharge. In-situ trials at Mindong No.1 Mine revealed that near-field processes involved cation exchange, mineral dissolution, and organic carbon mobilization, whereas the far-field accumulated refractory organics and microbial protein-like substances. Cross-zonal cation bridging exacerbates bio-chemical clogging. Low-disturbance pretreatment and zonal monitoring are recommended to ensure long-term groundwater sustainability.

Keywords: Mine water Managed Aquifer Recharge (MMAR), hydrochemical evolution, dissolved organic matter, secondary mobilization

Introduction

Coal remains fundamental to China's energy security, yet its distribution exhibits a severe spatial mismatch with water resources. The central and western regions hold nearly 90% of the national coal resources but possess limited water, situating coal-abundant areas predominantly in arid and semi-arid zones (Peng *et al.* 2015; Yuan 2023). As coal exploitation shifts westward, intensive deep mining severely disturbs overlying aquifers, leading to massive groundwater ingress and the loss of over 6 billion tons of groundwater through drainage-dominated hazard control measures (Gu *et al.* 2021). While current management emphasizes source protection and surface reuse, limited industrial water demand in western mining areas causes large volumes of treated mine water to be discharged as surface runoff. This permanent conversion of groundwater to surface water causes sustained depletion of regional groundwater systems. In ecologically fragile zones, this depletion manifests as persistent water level drawdowns, vegetation degradation, and severe spring desiccation (Wang *et al.* 2025). In intensely dewatered regions like the Huanglong mining area, maximum local drawdowns reaching 194.87 m compress aquifer storage space and diminish hydraulic conductivity, leading to the functional attenuation of the entire groundwater system (Fan *et al.* 2020).

To address these insidious environmental risks, this study proposes the Mine Water Managed Aquifer Recharge (MMAR) conceptual framework. By constructing a circulation pathway, MMAR aims to achieve sustainable water circulation by returning mine water to underground aquifers. Focusing on the complex biogeochemical risks associated with this system, an in-situ recharge trial was conducted at the Mindong No. 1 Mine. This study elucidates the mechanisms of environmental responses within the MMAR system, providing a scientific basis for developing risk management strategies based on geo-

chemical compatibility and facilitating the green transformation of water conservation technologies.

Mine water Managed Aquifer Recharge

To sustain the groundwater eco-environment amid the coal-water mismatch, this study proposes the Mine Water Managed Aquifer Recharge (MMAR) conceptual framework. MMAR utilizes engineering measures—including surface ecological infiltration, pressurized well-field recharge, and underground cross-aquifer redistribution—to construct a "Source-Treatment-Storage" closed loop. This approach returns mine water to underground systems, minimizing surface discharge (Fig. 1).

MMAR encompasses three primary recharge modes: (1) diverting and reallocating threatening, unentered groundwater in-situ via underground boreholes; (2) treating ingressed mine water for surface infiltration to sustain shallow ecological aquifers; and (3) injecting treated mine water ex-situ into primary water-supply aquifers via pressurized well fields. By reconstructing impaired flow fields, MMAR strives for near-zero discharge and the simultaneous remediation of mining hazards and ecosystems (Miao et al. 2025).

However, implementing MMAR in deep, complex environments creates a coupled system involving stress, flow, and geochemical processes, introducing multiple risks. Macroscopically, artificial flow field reconstruction may threaten underlying coal extraction. Microscopically, MMAR faces highly concealed biogeochemical environmental risks (Fakhreddine *et al.* 2021; Imig *et al.* 2022). Injecting treated mine water with different hydrochemical characteristics inevitably disrupts the native aquifer's dynamic equilibrium (Sun *et al.* 2020; Fakhreddine *et al.* 2021). This incompatibility makes the system susceptible to recharge pathway clogging and secondary hydrogeochemical deterioration (Antoniou *et al.* 2014; Fakhreddine *et al.* 2021). While hydrodynamic threats are manageable, delayed and potentially irreversible biogeochemical risks present a critical barrier.

Given the limited understanding of these water-rock interactions, conducting whole-process water quality evolution studies based on in-situ field trials is essential for scientifically identifying and managing MMAR environmental risks.

Materials and Methods

The Mindong No. 1 Coal Mine in the Yimin Coalfield experiences a considerable inflow of 500 to 600 m^3/h. The lack of effective recycling, juxtaposed against an arid climate with an annual evaporation of 1166 to 1284 mm, causes substantial resource wastage. The study area is underlain by two major aquifer systems: the Cretaceous Yimin Formation aquifer and the Quaternary pore aquifer

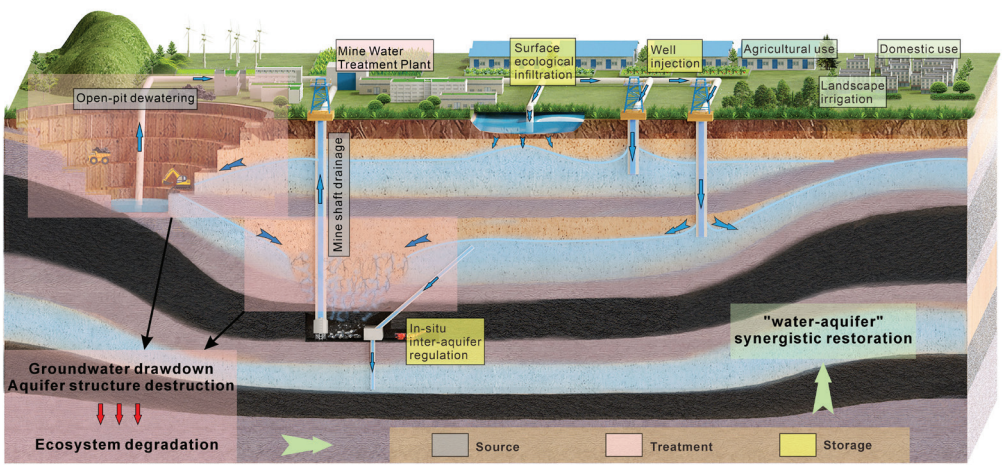

Figure 1 Conceptual model of the M-MAR system.

(average thickness 29.80 m). The Quaternary strata comprise upper silty-fine sands and lower sandy gravels. Hydraulic conductivity ranges from 58.17 to 114.09 m/d, and specific capacity ranges from 0.582 to 23.669 L/ (s·m). The phreatic groundwater flows from southeast to northwest (Fig. 2).

The Quaternary aquifer was selected for the recharge experiment. The system comprised an injection well (R1) and five monitoring wells (M2 to M6), supplied by a reservoir 350 m away. Continuous injection lasted 173.5 h, followed by a 65.5 h recovery period. Upon stabilization, the water level depth in R1 was 701.84 m. The monitoring wells achieved dynamic stability within 9 to 12 h, with water level increases of 0.75 to 1.39 m. Groundwater was sampled daily in triplicate, filtered (0.45 μm), stored in brown glass bottles, and analyzed within 24 h.

Water quality parameters, including pH, total hardness, turbidity, total dissolved solids, chloride, nitrate, nitrite, and ammonia nitrogen, were measured (Table 1). Dissolved organic matter was characterized using three-dimensional Excitation-Emission Matrix (EEM) fluorescence spectroscopy. The fluorescence dataset was subsequently decomposed using a three-component Parallel Factor Analysis (PARAFAC) model in MATLAB to identify underlying fluorescence components.

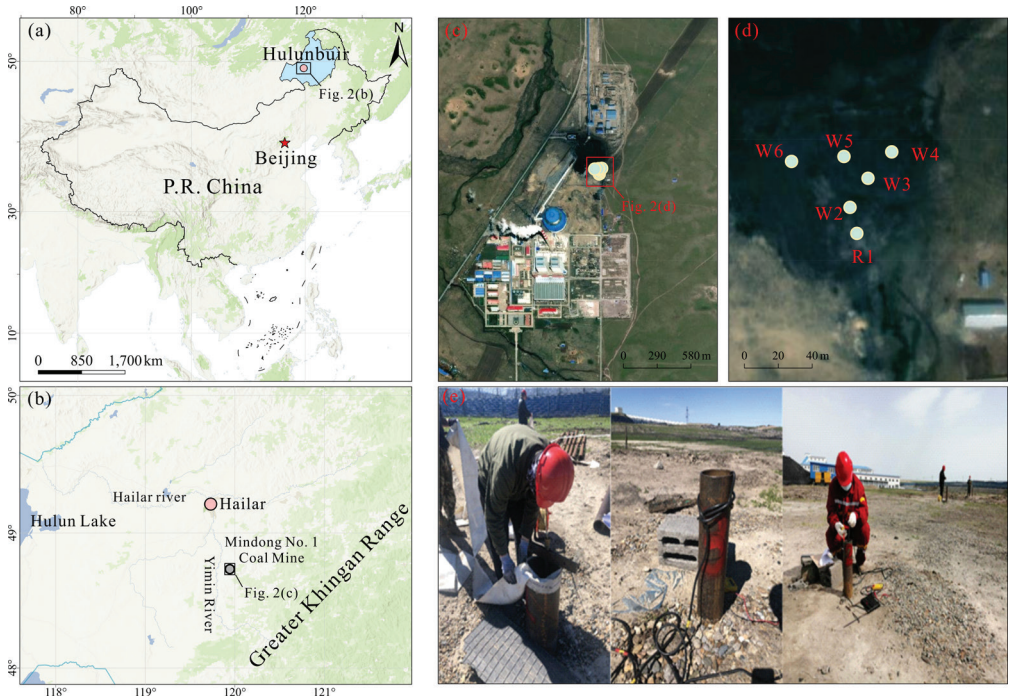

Figure 2 *Conceptual model of the M-MAR system.*

Table 1 *Determination methods of physical and chemical parameters.*

Test items	Unit	Testing method	Reference standard
pH		glass electrode method	DZ/T0064-1993/5
Total hardness	mg/L	Disodium EDTA titration	DZ/T0064-1993/15
TDS	mg/L	105 °C drying method	DZ/T0064-1993/9
Chloride	mg/L	silver nitrate titration	DZ/T0064-1993/50
Nitrate	mg/L	Thyme Powder Spectrophotometry	GB/T5750.5-2006/5.1

Results

Inorganic Hydrochemistry

Initially, pH in all monitoring wells declined, rebounding variably after 5 d. Pre-treated recharge water exhibited low total hardness (≈15 mg/L), whereas ambient groundwater exhibited high hardness. Hardness in most monitoring wells initially exceeded the source water, subsequently declining and stabilizing from 5 d onwards. Conversely, well W2 exhibited increasing hardness from 3 d, peaking at 155 mg/L on 7 d. Total dissolved solids followed an identical pattern, with W3 to W6 remaining low while W2 reached 316 mg/L by 7 d. Chloride concentrations remained below 250 mg/L (4 to 16 mg/L), though W2 maintained higher levels. Nitrate was low in the recharge water, but W2 displayed a short-term nitrate enrichment (peak 4.36 mg/L), likely originating from ammonium desorption and rapid nitrification.

Organic Composition

Dissolved organic carbon and chemical oxygen demand exhibited spatial disparities. After 2 d, dissolved organic carbon in W2 exceeded the recharge water but subsequently declined, while other wells displayed daily increases. Chemical oxygen demand in W2 was initially anomalously high before decreasing; conversely, levels in W2 to W5 increased from 4 d. These spatiotemporal patterns indicate the secondary mobilization of endogenous organic matter triggered by injection. Parallel factor analysis of excitation-emission matrix data identified three primary fluorescent components. Component C1 (Ex/Em = 240/380 nm) corresponds to a highly mobile, terrestrial fulvic acid-like substance (Harjung *et al.* 2019). Component C2 (Ex/Em = 265/440 nm) is a terrestrial humic-like component characterized by high aromaticity (Chen *et al.* 2017; Tang *et al.*

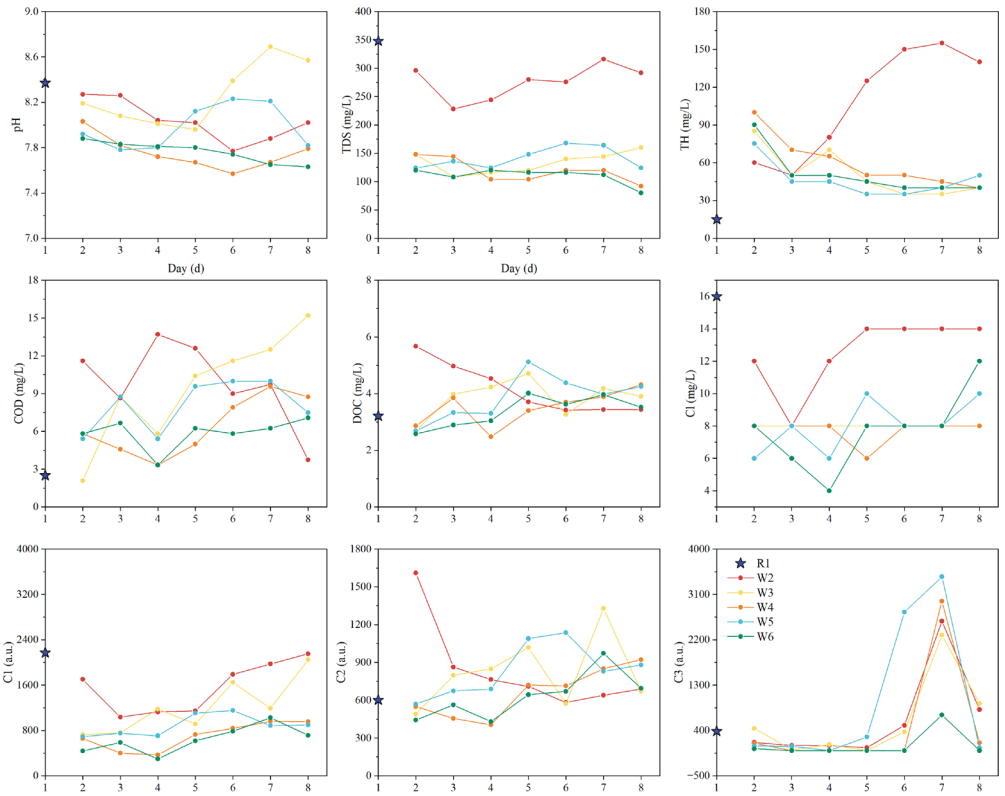

Figure 3 Temporal variations of major hydrochemical components.

2024). Component C3 (Ex peak ≈300 nm, Em peak ≈340 nm) is a protein-like component derived from biological activity (Yamashita *et al*. 2010; Eder *et al*. 2022).

Discussion

Hydrochemical Response Characteristics

Maintaining a constant recharge rate of 12 L/ min in the injection well (R1) raised the groundwater level from 702 to 715 m, inducing a substantial hydraulic gradient. Wells W2 to W6 exhibited a synchronous rapid rise on the first day, followed by a slower ascent governed by the superimposed native flow field and recharge mound. Hydrochemical evolution demonstrated a spatiotemporal lag between pressure propagation and solute transport (Fig. 3). Based on chloride and total dissolved solids variations, the aquifer comprises two distinct regions. The rapid response zone (near-field, R1 to W2) showed immediate chloride and total dissolved solids responses, indicating advection-dominated rapid mixing where near-field hydrochemistry became controlled by the injectant. The transitional zone (far-field, W3 to W6) showed solute concentrations remaining low and increasing only around 5 d, demonstrating that the solute transport front lagged the pressure wave. Intense hydraulic disturbance induced anomalous geochemical responses. In the transitional zone, total hardness declined due to dilution by the injected soft water (≈15 mg/L). Conversely, in the rapid response zone (W2), total hardness rapidly spiked to 150 mg/L between 5 d and 8 d. This anomaly, alongside a rapid surge of nitrate, is attributed to intensified cation exchange (displacing adsorbed Ca^{2+} and Mg^{2+}) and carbonate mineral dissolution driven by high flow velocities and the Na-rich, carbonate-undersaturated injectant. Consequently, near-field hydrochemistry is dominated by mineral leaching and cation exchange, masking physical dilution.

Spatiotemporal Evolution of DOM

Dissolved organic matter evolution diverged markedly from theoretical mixing predictions. Component C1 (fulvic acid-like) maintained high levels in the rapid response zone and accumulated in the transitional zone, eventually approaching source water levels (>2000 a.u.) and dominating the aquifer background (>50%). Component C2 (humic-like) mirrored this accumulation. Initially, C2 in W2 exceeded source water levels, indicating that hydraulic scouring caused the secondary mobilization of adsorbed humic acids. While mixing influences organic content, the accumulation of C1 and C2 over time and distance dominates. Conversely, the protein-like component C3 exhibited reactive generation, surging in both zones around 5 d to 6 d (reaching 3451 a.u. in W5). Because C3 was negligible in the source water, this burst precludes physical mixing. Initially, hydraulic disturbance mobilized endogenous organic carbon in the near-field (chemical oxygen demand reached 11.6 mg/L). This mobilized carbon was transported downstream, providing abundant substrate for microbes in the transitional zone. Furthermore, the upstream release of Ca^{2+} and Mg^{2+} stimulated microbial extracellular polymeric substance secretion. Therefore, the release of hardness components and endogenous organic carbon jointly drove the explosive growth of metabolic by-products (C3), marking a shift to microbially dominated processes.

Conceptual Model of Environmental Response in MMAR

Based on these findings, a conceptual model of the MMAR groundwater environmental response was established (Fig. 4). Discharged mine water, despite pre-treatment, retains ionic and organic disparities compared to native groundwater. This incompatibility creates two spatial response zones. In the rapid response zone, forced convection and inorganic re-equilibration dominate. The injection of Na-dominated, carbonate-undersaturated water triggers vigorous cation exchange and mineral dissolution, displacing Ca^{2+} and Mg^{2+}. Concurrently, hydraulic scouring desorbs endogenous organic carbon, causing an instantaneous release of organic load. This secondary mobilization masks dilution, creating a near-field hydrogeochemical anomaly. In the transitional zone, the dominant process shifts to organic accumulation and biogeochemical transformations. Refractory humic

substances (C1/C2) migrate to the far-field, while endogenous organics from the near-field fuel microbial activity, leading to an explosive growth of protein-like components (C3). A critical cross-zonal coupling occurs where high concentrations of Ca^{2+} and Mg^{2+} from the near-field interact with C1 and C3 via cation bridging, promoting organic colloid flocculation and biofilm consolidation. This exposes the far-field to severe bio-chemical composite clogging risks.

Environmental Implications and Risk Control Strategies

In-situ trials validate MMAR's hydraulic feasibility for elevating groundwater levels without irreversible flow field alterations. However, geochemical incompatibility necessitates a paradigm shift to prioritize geochemical compatibility alongside hydraulic loading. Pre-treatment should adhere to a minimal interference principle. Rather than pursuing absolute purity, it should modulate the ionic strength and sodium adsorption ratio of the recharge water to match the receiving aquifer, minimizing matrix dissolution and pollutant desorption driven by cation exchange. Enhanced removal of colloids and dissolved organic matter is also recommended to eliminate carriers that facilitate pollutant co-transport. Furthermore, long-term MMAR operation is threatened by deep bio-chemical composite clogging. Divalent cations (Ca^{2+}/Mg^{2+}) promote suspended particle flocculation and stimulate microbial extracellular polymeric substance secretion, forming recalcitrant clogging layers. Consequently, operational management requires a zonal warning strategy. In the near-field, abrupt changes in hardness and total dissolved solids should trigger interventions, such as adjusting injection rates, to suppress cation exchange. In the far-field, lagged peaks in protein-like fluorescence (C3) or chemical oxygen demand serve as precursors to deep bio-clogging, necessitating timely responses like backwashing or applying bacteriostats to destabilize biofilms.

Conclusion

This study proposes the Mine Water Managed Aquifer Recharge (MMAR) theoretical framework, utilizing in-situ trials, hydrochemical analysis, and three-dimensional fluorescence spectroscopy to reveal groundwater evolutionary mechanisms. By integrating multiple geoscientific disciplines, this "source–treatment–storage" pathway enables near-zero mine water discharge, addressing regional coal-water constraints. Field trials at the Mindong No. 1 Mine elucidated specific biogeochemical patterns during MMAR implementation. In

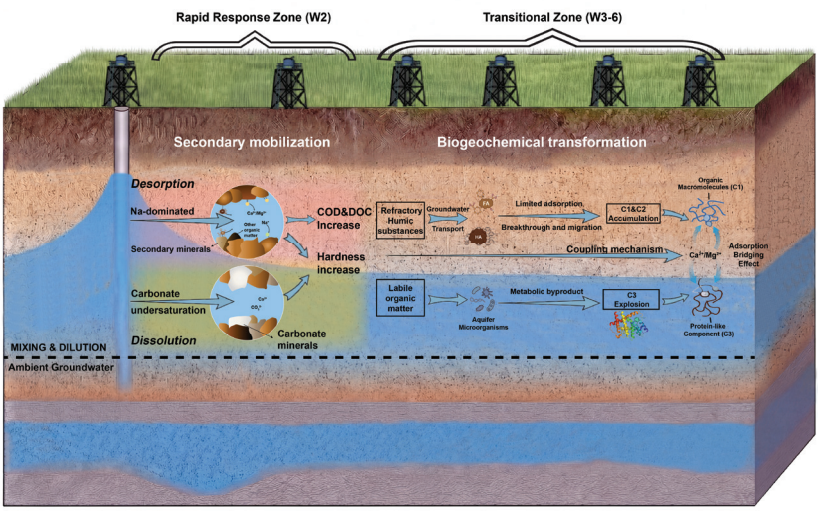

Figure 4 *Conceptual model of environmental responses to M-MAR.*

the near-field region, strong ion exchange and the secondary mobilization of inorganic and organic components occur. Conversely, in the far-field region, hardness ions interact with protein-like components via complexation and bridging, synergistically contributing to bio-chemical clogging. These mechanisms highlight the necessity of coupled water quality and quantity regulation. Implementing low-disturbance pre-treatment alongside zonal monitoring strategies effectively mitigates clogging risks, ensuring the long-term stability and groundwater sustainability of MMAR systems.

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