Postprint: Study on Shallow Groundwater Recharge in the Beishan Area Based on Environmental Tracer Chloride

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Abstract

Groundwater recharge research constitutes one of the critical research components for site selection and site evaluation of deep geological repositories for high-level radioactive waste. The Beishan area in Gansu Province serves as the preferred preselected candidate region for China' s high-level radioactive waste geological disposal repository. To investigate the groundwater recharge characteristics in this region, the shallow groundwater recharge rate in the Beishan area was determined using the environmental tracer chloride. The results demonstrate that: (1) Overall, the chloride mass balance method exhibits good applicability in the Beishan area. (2) The vertical recharge rate of shallow groundwater calculated by the chloride mass balance method based on the unsaturated zone ranges from 0.07~2.03 mm · a-1 in valley basins with high permeability, with an average value of approximately 1.0 mm · a-1. (3) The chloride mass balance method based on the saturated zone yields a long-term average infiltration recharge rate of 0.25 mm · a-1 for shallow groundwater in the Beishan area, which accounts for less than 0.5% of the long-term average precipitation. These findings can provide a scientific basis for site selection and site evaluation of China' s high-level radioactive waste geological disposal repository.

Full Text

Preamble

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Abstract: Hydrogeological conditions constitute one of the most critical factors in site selection and safety assessment for high-level radioactive waste (HLW) disposal repositories. Groundwater recharge research is of paramount importance in hydrogeological studies. The Beishan area in Gansu Province, China, represents a priority preselected region for China' s HLW disposal repository. Located in the northern Hexi Corridor of Gansu Province, approximately 70 km south of Yumen Town, this study investigates groundwater recharge rates in the Beishan area using the chloride mass balance (CMB) method applied to both the unsaturated and saturated zones. Considering the thickness and lithology of the unsaturated zone, typical profiles were selected based on available fieldwork conditions, resulting in four representative profiles across the Beishan area, situated in Suanjingzi, Shazaoyuan, and Xinchang respectively. Additionally, 45 shallow groundwater samples were successfully collected, with most wells having depths less than 10 meters and relatively uniform spatial distribution. The results indicate: (1) The CMB method demonstrates good applicability in the Beishan area. Groundwater recharge rates derived from the unsaturated zone CMB method range from 0.07 to 2.05 mm · a ^{1}, with all profiles located in gully basins characterized by relatively high permeability. The saturated zone CMB method yields a recharge rate of approximately 0.26 mm · a ^{1}, representing only 0.40% of the average annual precipitation. (2) The unsaturated zone CMB method has limitations in areas with high background chloride values, necessitating consideration of alternative methods such as artificial tracers, ^{3}H, bromide, water-table fluctuation methods, and water-budget models. (3) Atmospheric precipitation chloride concentration significantly influences results as a background input parameter. (4) Given the complexity and uncertainty inherent in groundwater recharge research, this study recommends investigating additional methods—including artificial tracers, water-table fluctuation methods, and Darcy' s method—to complement the current findings. This research marks the first determination of groundwater recharge rates in the Beishan area, providing valuable insights for HLW repository site selection and safety assessment, as well as for future underground laboratory construction.

Keywords: groundwater recharge; high-level radioactive waste disposal; environmental tracer; chloride mass balance (CMB) method

2. Materials and Methods

2.1 CMB Method

The fundamental principle of the chloride mass balance (CMB) method for estimating groundwater recharge is based on the conservative behavior of chloride ions in groundwater systems. The method assumes that chloride originates primarily from atmospheric deposition and that its concentration in groundwater reflects the balance between atmospheric input and water flux. The recharge rate can be calculated using the following relationship:

$$R = \frac{P \cdot C_p}{C_g}$$

where R represents the groundwater recharge rate (mm • a ^{1}), P denotes precipitation (mm • a ^{1}), C_p indicates chloride concentration in precipitation (mg • L ^{1}), and C_g signifies chloride concentration in groundwater (mg • L ^{1}).

The CMB method offers several advantages for arid and semi-arid regions: (1) Chloride is chemically stable and non-volatile, making it an ideal conservative tracer; (2) The method integrates long-term recharge processes, providing representative average rates; (3) It is cost-effective and relatively simple to implement compared to other hydrogeological methods.

Four typical profiles were established in the study area, designated as TC-2, TC-3, TC-4, and TC-5. Profile locations were selected based on geomorphological features, accessibility, and representativeness of regional hydrogeological conditions. Soil samples were collected at 10-20 cm intervals to depths ranging from 1.5 to 2.5 meters. Shallow groundwater samples were obtained from hand-dug wells and monitoring wells with depths generally less than 10 meters. All samples were analyzed for moisture content, pH, soluble salt content, and chloride concentration using standard laboratory procedures.

3. Results

3.1 CMB Method Results

3.1.1 Profile Characteristics **TC-2 Profile:** Located in a low-lying alluvial fan deposit, this profile exhibited relatively uniform sandy loam texture throughout the 1.5 m depth. Moisture content ranged from 3% to 8% by volume, with higher values observed in the upper 0.5 m. Soil pH remained consistently alkaline, varying between 8.2 and 8.7. Soluble salt content showed moderate levels, with chloride concentrations ranging from 150 to 450 mg • L ^{1} in soil water extracts.

TC-3 Profile: Situated in a transitional zone between alluvial and proluvial deposits, this profile displayed more heterogeneous lithology, with alternating layers of coarse sand and gravel. Moisture content was generally lower, averaging 2-5%, while pH values were slightly higher (8.5-9.0). Chloride concentrations in soil water showed greater variability, ranging from 200 to 800 mg · L ^{1}, reflecting the influence of evaporative concentration processes.

TC-4 Profile: Positioned in a higher elevation area with bedrock outcrops nearby, this profile featured a thin (0.15 cm) surface crust underlain by weathered granite and sandstone. Moisture content was notably low (<2% in the deeper sections), while pH values exceeded 8.5 throughout the profile. Chloride concentrations displayed a distinct peak at 1.2 m depth, reaching values of 12,340-77,681 mg · L ^{1}, indicating significant evaporative enrichment and minimal leaching.

[Figure 4: see original paper] Lithology, moisture content, pH, and soluble salt content of soil water in TC-2 profile

[Figure 5: see original paper] Lithology, moisture content, pH, and soluble salt content of soil water in TC-3 profile

[Figure 6: see original paper] Lithology, moisture content, pH, and soluble salt content of soil water in TC-4 profile

3.1.2 Recharge Rate Calculations Groundwater recharge rates calculated using the unsaturated zone CMB method yielded values of 1.54 mm · a ^{1} and 0.67 mm · a ^{1} for profiles TC-2 and TC-3, respectively. The TC-4 profile, located in an area with extremely high background chloride values, produced an anomalously low recharge estimate of 0.07 mm · a ^{1}, highlighting the method' s limitations under such conditions.

The saturated zone CMB method, applied to shallow groundwater samples, provided an average recharge rate of 0.26 mm · a ^{1} across the study area. This value represents only 0.40% of the average annual precipitation (approximately 65 mm · a ^{1}), indicating extremely low recharge characteristic of hyper-arid environments.

The chloride deposition rate was estimated at 3.17 mg · m ^{2} · a ^{1} based on atmospheric deposition measurements, while the average chloride concentration in precipitation was determined to be 65.40 mg · L ^{1}. These parameters served as critical input values for the CMB calculations.

3.2 Discussion of CMB Method

3.2.1 Isotopic Evidence Stable isotope analysis (D and ^{1} O) of shallow groundwater samples provides independent verification of recharge mechanisms. The D- ^{1} O relationship [Figure 7: see original paper] shows that most groundwater samples plot along the local meteoric water line, indicating modern meteoric origin without significant evaporation effects. However, some samples from high-chloride areas exhibit isotopic enrichment, suggesting evaporative concentration prior to recharge.

The isotopic composition of groundwater samples ranged from ^{1}O = -8.5‰ to -6.2‰ and D = -65‰ to -45‰, consistent with precipitation in the region. The absence of significant isotopic deviation from the meteoric water line supports the applicability of the CMB method, as it indicates minimal evaporative fractionation during recharge.

[Figure 7: see original paper] Plot of D versus ^{1}O for shallow groundwater

The relationship between chloride concentration and recharge rate follows an inverse power function, as predicted by the CMB equation. Areas with chloride concentrations exceeding 2,000 mg · L^{1} consistently show recharge rates below 0.5 mm · a^{1}, while lower chloride areas (<500 mg · L^{1}) exhibit recharge rates up to 2.0 mm · a^{1}.

The CMB method' s limitations become apparent in areas with high background chloride values, where the signal-to-noise ratio is low. In such cases, alternative methods should be considered, including artificial tracer injection, ^{3}H dating, bromide tracing, water-table fluctuation analysis, and water-budget modeling. The integration of multiple methods would provide more robust recharge estimates and reduce uncertainty.

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