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Research Article

Mechanisms of irrigation water recharge in the Kongque River Irrigation District of Xinjiang, China

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Abstract: Understanding the infiltration process and quantifying recharge are critical for effective water resources management, particularly in arid and semi-arid regions. However, factors influencing on recharge process under different land use types in irrigation districts remain unclear. In this study, a Brilliant Blue FCF dye tracer experiment was conducted to investigate infiltration pathways under the cotton field, pear orchard, and bare land conditions in the Kongque Rive Irrigation District of Xinjiang, China. Recharge rates were estimated using the chloride mass balance method. The results show that the average preferential flow ratio was highest in the bare land (50.42%), followed by the cotton field (30.09%) and pear orchard (23.59%). Matrix flow was the dominant infiltration pathway in the pear orchard and cotton field. Irrigation method was a primary factor influencing recharge rates, with surface irrigation promoting deeper infiltration compared to drip irrigation. Under the drip irrigation mode, the recharge of cotton fields ranged from 23.47 mm/a to 59.16 mm/a. In comparison, the recharge of surface irrigation in pear orchards contributed between 154.30 mm/a and 401.65 mm/a. These findings provide valuable insights into soil water infiltration and recharge processes under typical land use conditions in the Kongque River Irrigation District, supporting improved irrigation management and sustainable water resource utilization.

Keywords: Infiltration; Matrix flow; Chloride mass balance; Recharge; Kongque River Irrigation District; Arid regions

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Introduction

The arid and semi-arid areas of northwestern China account for around one-third of the country's land area in China (Zhong et al. 2025). These regions are characterized by low rainfall, high-intensity evaporation, limited surface water availability, and heavy reliance on groundwater resources, which are crucial for local communities and agricultural production. Groundwater recharge in such areas primarily occurs through surface water infiltration, irrigation return flow, and rainfall recharge (Wang et al. 2018). Surface water has historically been the dominant source of groundwater recharge in the Kongque River Irrigation District, China (Zhang et al. 2021a), as the rapid socio-economic development and increasing water demand have significantly improved the importance of irrigation induced recharge. Understanding the dynamics of recharge is important for predicting the influence of climate and land use/cover changes on groundwater resources, and for the assessment of sustainable levels of groundwater extraction (Gong et al. 2023).

The Kongque River Irrigation District, located in a continental arid climate zone, is a key region

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for ecological conservation and agricultural production in Xinjiang, China. Cotton and pear are the predominant crops, and their cultivated areas have expanded rapidly in recent years, leading to a rise in the consumption of irrigation water. Drip irrigation is a common practice in cotton fields, while pear orchards primarily rely on conventional surface irrigation methods. Although drip irrigation enhances water use efficiency in the short term, long-term use may reduce soil water retention in the vadose zone and alter the hydraulic connectivity between shallow and deep soil layers in arid and semi-arid regions (Porhemmat et al. 2018). Despite the importance of irrigation water as a source of recharge, limited studies have specifically addressed this process in the Kongque River Irrigation District. Zhang (2015) reported that the recharge ranged from 181.80 mm/a to 687.58 mm/a, with irrigation return flow contributing between 12.37% and 28.79% of total recharge in the downstream of Kongque River Irrigation District, as determined by the chloride mass balance. Du (2009) set up HYDRUS-1D models to estimate recharge from the irrigation water. The recharge could account for 14%–32% of irrigation water under deep water table depth conditions in the Yanqi Basin, which is located upstream of the Kongque River Basin. However, no observed data was used to validate the model, and the focus was exclusively on the surface irrigation method. Therefore, there is a pressing need to investigate the infiltration process and influencing factors of recharge under different irrigation methods in the Kongque River Irrigation District. A comprehensive understanding of the infiltration process is essential to support sustainable water resource management and optimize irrigation practices in arid regions (Zhang et al. 2021b).

Infiltration in the vadose zone generally occurs via matrix flow or preferential flow pathways. Land use/cover plays a critical role in shaping the infiltration process. For example, woody vegetation generally enhances preferential flow due to deeper and more developed root systems (Lv et al. 2019). Chu et al. (2023) found that preferential flow was evident in paddy fields and forestlands. Guan et al. (2023) observed significant spatial variability in preferential flow across forest stands in the Karst region of Southwest China, influenced by soil properties such as nutrient levels. Qiu et al. (2023) demonstrated that vegetation restoration could improve soil infiltration and increase preferential flow in the Loess Plateau, and the most significant effects on soil infiltration and preferential flow have been observed in shrublands. Furthermore, Chen et al. (2022) reported that grazing bans significantly increased preferential flow under the condition of grassland. Therefore, the infiltration pathways under different land use/cover conditions exist differently.

Given the above-mentioned research gaps, this study used the dye tracer method to explore the infiltration pathway of water flow under typical land use conditions (cotton field, pear orchard, and bare land). The chloride mass balance was employed to estimate recharge in the Kongque River Irrigation District of Xinjiang, China. The main goal was to clarify the infiltration process from irrigation water under typical land use conditions and identify key factors influencing recharge, including soil properties, land use types, and irrigation methods. These results contribute to a deeper understanding of irrigation recharge for the sustainable development and protection of regional water resources. This study also provides recommendations for optimizing agricultural irrigation practices in the Kongque River Irrigation District.

1 Material and methods

1.1 Study area

The Kongque River Irrigation District is located in the southern Tien Shan Mountains and the northeastern edge of the Tarim Basin, adjacent to the Taklamakan Desert. The region exhibits a northwest-to-southeast slope and is characterized by an arid climate with low annual rainfall, large temperature variations, and abundant sunshine. The topography is highly variable, particularly in the mountainous regions at elevated altitudes. The range of elevations is from a maximum of 4,666 meters to a minimum of 770 meters. The main water sources of this region include an influx of water from the Kaidu River and snowmelt from the Tien Shan Mountains. The native crops cultivated are cotton and pear, with cotton being predominantly planted in the middle and lower reaches, and pear orchards concentrated in the upper regions.

1.2 Methods

1.2.1 Dye tracer experiment

We designed dye tracer experiments in the Kongque River Irrigation District to investigate the infiltration pathway of water flow in the vadose zone in July 2021. Brilliant Blue FCF was used as a dye tracer. Three experimental sites were set up (cotton field, pear orchard, and bare land). Each site covered an area of 1 square meter. A total of 150 L of brilliant blue FCF solution, at a concentration of 2.5 g/L, was evenly applied to each site. To prevent the influence of evaporation, every site was covered with plastic film. After 48 hours, the vertical soil profiles were excavated at the location of 10 cm, 30 cm, and 50 cm in every experimental site (Fig. 1). These three profiles were labeled as follows: M10, M30, and M50 in the cotton field; X10, X30, and X50 in the pear orchard; and L10, L30, and L50 in the bare land. A high-resolution camera was used to photograph these vertical profiles, and measurements were taken for subsequent image analysis. Soil samples were also collected at various depths using ring knives to analyze soil properties (Table 1).

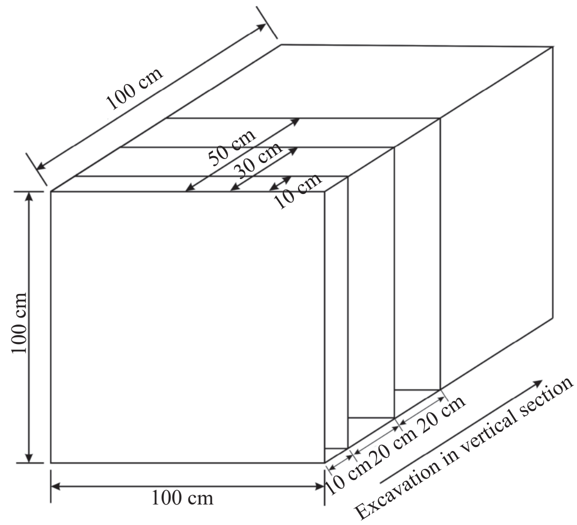

Fig. 1 Schematic diagram of the dye tracer experiment

The experimental procedure included the following steps: (1) Image cropping and correction: The stained images of the 100 cm × 100 cm vertical soil profiles were standardized to a resolution of 3,000 × 3,000 pixels. To address the issue of uneven illumination, which has the potential to compromise the accuracy of the data, adjustments were made to the image parameters. These adjustments included alternations to saturation, hue, and threshold levels; (2) Color substitution and binarization: The corrected images were binarized to clearly distinguish between stained and unstained regions, which could effectively determine the pathway of infiltration water. The pixel counts for the black (stained) and white (unstained) areas were analyzed.

(1) The ratio of stained area

The stained area ratio (D_c) is defined as the ratio of the soil profile stained area to the total soil profile area, thereby reflecting the overall distribution of stained water flow.

$$D_c = \frac{D_S}{D_T} \times 100 \tag{1}$$

Where: D_c is the ratio of stained area (%), D_S is the area of stained area (cm^2), and D_T is the area of the soil profile (cm^2).

(2) Depth of matrix flow

The matrix flow depth (U_F) is the depth of a minimum of 80% stained area. The larger the U_F, the greater the lag of preferential flow in the soil, thus indicating that the path of matrix flow is deeper (Van Schaik, 2009).

(3) Preferential flow ratio

The preferential flow ratio (P_F) is the fraction of total infiltration that flows through the preferential flow pathway (Van Schaik, 2009).

$$P_F = \left(1 - \frac{W \times U_F}{TotStAr}\right) \times 100 \tag{2}$$

Where: P_F is the preferential flow ratio (%), U_F is the depth of matrix flow (cm), W is the horizon-

Table 1 Soil properties

Land use type	Depth/cm	Soil bulk density/g/cm^3	Clay/%	Silt/%	Sand/%	Soil type
Cotton field	10.00	1.28	9.49	39.43	51.08	Loam
	20.00	1.45	10.32	47.21	42.47	Loam
	30.00	1.50	12.25	75.02	12.73	Silt loam
Bare land	10.00	1.20	2.69	6.06	91.25	Sand
	30.00	1.18	11.79	34.06	54.15	Sandy Loam
	50.00	1.29	12.99	40.62	46.39	Loam
	70.00	1.27	2.70	55.63	41.67	Silt loam
Pear orchard	10.00	1.32	14.92	39.36	45.72	Loam
	20.00	1.07	15.43	35.59	48.98	Loam
	30.00	1.28	1.40	14.17	84.43	Sandy Loam
	40.00	1.42	4.56	50.70	44.74	Silt loam

tal width of the profile (cm), and $TotStAr$ is the total stained area in the soil profile (cm^2).

(4) Length index

The length index (L_i) of preferential flow describes the heterogeneity of dye penetration (Hou et al. 2023).

$$L_i = \sum_{i=1}^{n} |D_{c(i+1)} - D_{ci}| \quad (3)$$

Where: L_i is the preferential flow length index (%), $D_{c(i+1)}$ and D_{ci} are the ratios of the stained area at soil profile layers of i+1 and i (%), and n is the number of vertical soil layers in the soil profile. We considered 10 pixels along with the soil vertical profile as one layer. The Pearson correlation coefficient was employed to investigate the relationship between the length index and various soil properties. Statistical significance was determined at the $p < 0.01$ level.

1.2.2 Samples collection

From July to August 2021, we conducted soil samples across 29 soil profiles, collecting samples at 20 cm intervals. Additionally, we obtained one irrigation water sample for every profile, excluding profiles L1, X1, and X2. Fig. 2 shows the spatial distribution of these soil profiles, while Table 2 provides detailed information on soil profile depths, land use types, and irrigation water sources.

1.2.3 Chloride mass balance

The Chloride Mass Balance (CMB) was used to estimate recharge. The application of the CMB was based on several key assumptions (Cook and Brunner, 2025): (1) The system is at a steady state and runoff is negligible. (2) The primary sources of chloride are rainfall, dry deposition, and irrigation. The recharge rate was calculated using the following equation (Zhang et al. 2023):

$$P \times Cl_P + I \times Cl_I + D = R \times Cl_s \quad (4)$$

Where: R is the recharge (mm/a), P is rainfall (mm/a), I is irrigation (mm/a). Cl_P, Cl_I, and Cl_s are the average chloride concentration of the rainfall, irrigation water, and soil water (mg/L), respectively. D is the dry deposition flux of chlorine ($mg/(m^2 \cdot a)$). The primary sources of chloride in the Kongque River Irrigation District are rainfall, dry deposition, and irrigation water.

(1) Rainfall: The region experiences an average annual rainfall of 55.36 mm. The average chloride concentration in rainwater samples is 25.00 mg/L, corresponding to an annual chloride input of 1,384.00 $mg/(m^2 \cdot a)$ via rainfall (Zhang, 2015).

(2) Dry deposition: The average chloride concentration in a dry deposition is 4.00 mg/L, and the dry deposition flux of chlorine is 3,940.00 $mg/(m^2 \cdot a)$ (Zhang, 2015).

(3) Irrigation: Groundwater serves as the primary irrigation water source in the research area, though the river is used in certain regions. For farmlands irrigated with groundwater, the chloride concentrations of nearby well water samples were used to represent the input values. In contrast, areas reliant on river water utilized chloride concentrations obtained from surface water samples collected near irrigation sites. Pear orchards employ large-scale surface irrigation methods, with annual irrigation volumes ranging from 800.00 mm to 1,040.00 mm. Cotton fields, however, are irrigated via drip irrigation methods, requiring significantly lower annual volumes (150.00–240.00 mm).

2 Results

2.1 Infiltration process

2.1.1 Maximum stained depth

As shown in Fig. 3, the maximum stained depth,

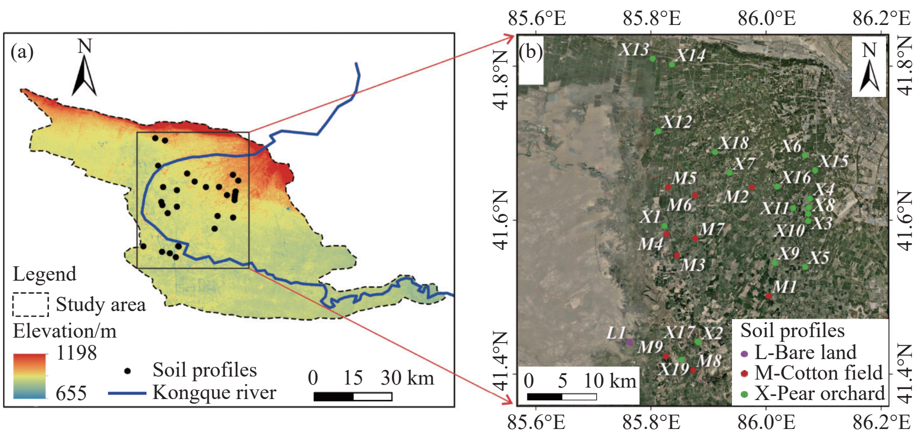

Fig. 2 (a) Elevation of Kongque River Irrigation District; (b) Location of soil profiles

Table 2 Detailed information of soil profile (Note that 'X' means pear orchard sites, 'M' means cotton field sites, and 'L' means bare land site)

Soil profiles	Sampling depth/cm	Land use type	Water sources
L1	100	Bare land	Rainfall
M1	220	Cotton field	Rainfall and confined water
M2	220	Cotton field	Rainfall and confined water
M3	220	Cotton field	Rainfall and confined water
M4	220	Cotton field	Rainfall and confined water
M5	220	Cotton field	Rainfall and confined water
M6	220	Cotton field	Rainfall and confined water
M7	200	Cotton field	Rainfall and confined water
M8	400	Cotton field	Rainfall and river
M9	220	Cotton field	Rainfall and river
X1	220	Pear orchard	Rainfall
X2	220	Pear orchard	Rainfall
X3	280	Pear orchard	Rainfall and confined water
X4	140	Pear orchard	Rainfall and confined water
X5	220	Pear orchard	Rainfall and confined water
X6	200	Pear orchard	Rainfall and confined water
X7	220	Pear orchard	Rainfall and confined water
X8	500	Pear orchard	Rainfall and river
X9	400	Pear orchard	Rainfall and river
X10	280	Pear orchard	Rainfall and river
X11	280	Pear orchard	Rainfall and river
X12	280	Pear orchard	Rainfall and river
X13	100	Pear orchard	Rainfall and river
X14	220	Pear orchard	Rainfall and river
X15	180	Pear orchard	Rainfall and river
X16	220	Pear orchard	Rainfall and river
X17	220	Pear orchard	Rainfall and river
X18	220	Pear orchard	Rainfall and river
X19	220	Pear orchard	Rainfall and river

was significantly greater in the bare land compared to the cotton field and pear orchard. Specifically, the maximum stained depths in the bare land consistently exceeded 50.00 cm, whereas in the cotton field and pear orchard, they ranged from 27.00 cm to 45.00 cm. Table 3 shows detailed maximum stained depths across observed profiles in every experimental site. In the bare land, the stained depths were 50.00 cm at L10, 62.00 cm at L30, and 67.20 cm at L50. In the cotton field, the maximum stained depths were 36.00 cm at M10, 27.00 cm at M30, and 28.00 cm at M50. In the pear orchard, the depths were 44.00 cm at X10, 45.00 cm at X30, and 39.00 cm at X50. The average maximum stained depths were 59.73 cm in the bare land, 42.67 cm in the pear orchard, and 30.33 cm in the cotton field.

2.1.2 Stained area ratio

Fig. 4 shows the distribution of stained areas at different soil profiles. As the stained area ratios increase, the spatial extent of tracer distribution also expands, reflecting faster water infiltration. According to Table 3, the stained area ratios for bare land profiles were 10.58% (L10), 27.73% (L30), and 29.70% (L50). In the pear orchard, the ratios were 19.25% (X10), 20.05% (X30), and

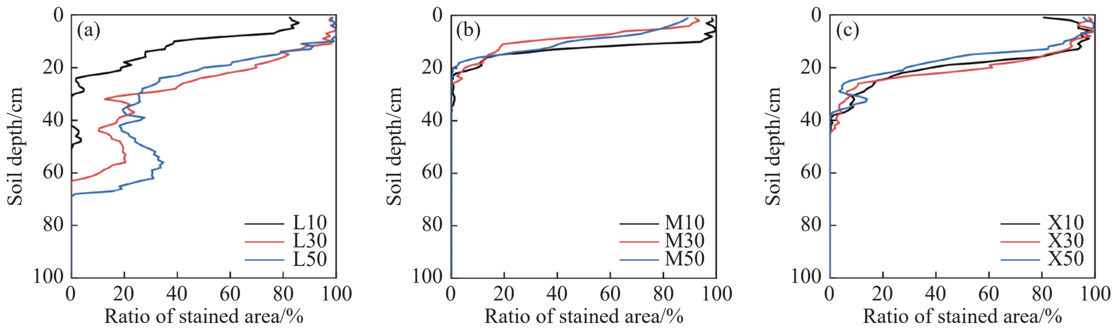

Fig. 3 Distribution of stained area ratio across soil profiles under the band land, cotton field, and pear orchard conditions (a, Bare land; b, Cotton field; c, Pear orchard)

Table 3 The maximum stained depth and preferential flow indices (stained area ratio, matrix flow depth, preferential flow ratio, and length index)

Site name	Vertical profile	Maximum stained depth/cm	Stained area ratio/%	Matrix flow depth/cm	Preferential flow ratio/%	Length index/%
Bare land	L10	50.00	10.58	5.00	52.74	112.52
	L30	62.00	27.73	16.00	42.30	170.28
	L50	67.20	29.70	13.00	56.23	174.70
	Average	59.73	22.67	11.33	50.42	152.50
	Standard deviation	6.50	8.06	4.22	5.00	26.70
Cotton field	M10	36.00	12.63	10.00	20.82	116.49
	M30	27.00	8.41	5.00	40.55	100.18
	M50	28.00	9.07	4.00	55.90	90.12
	Average	30.33	10.03	6.33	30.09	102.26
	Standard deviation	3.80	1.73	2.40	12.20	9.49
Pear orchard	X10	44.00	19.25	15.00	22.08	130.37
	X30	45.00	20.05	15.00	25.19	129.25
	X50	39.00	17.00	13.00	23.51	131.42
	Average	42.67	18.77	14.33	23.59	130.35
	Standard deviation	2.44	1.29	0.89	1.27	0.73

17.00% (X50). In the cotton field, the stained area ratios were the lowest, with values of 12.63% (M10), 8.41% (M30), and 9.07% (M50). On average, the stained area ratios were 22.67% in the bare land, 18.77% in the pear orchard, and 10.03% in the cotton field. Our results indicate that the infiltration rate of bare land was the highest, followed by the pear orchard, while the cotton field had the lowest rates. The observed differences in infiltration rates demonstrate the significant influence of land use on soil water movement.

2.1.3 Matrix flow depth

Table 3 shows the results of the matrix flow depth. In the bare land, the matrix flow depths were 5.00 cm (L10), 16.00 cm (L30), and 13.00 cm (L50), with an average of 11.33 cm. In the pear orchard, depths were 15.00 cm (X10), 15.00 cm (X30), and 13.00 cm (X50), averaging 14.33 cm. In the cotton field, the depths were 10.00 cm (M10), 5.00 cm (M30), and 4.00 cm (M50), with an average of 6.33 cm. These results indicate that matrix flow depth is the shallowest in the cotton field, whereas both pear orchard and bare land display deeper infiltration zones, with average matrix flow depths consistently exceeding 10.00 cm. This suggests that in the cotton field, water infiltration is largely restricted to the upper 0–10.00 cm of soil, whereas under the same irrigation condition, deeper infiltration occurs in the pear orchard and bare land.

2.1.4 Preferential flow ratio

Image analysis results for preferential flow ratios are shown in Table 3. Under the bare land condition, the preferential flow ratios for L10, L30, and L50 were 52.74%, 42.30%, and 56.23%, respectively. In the pear orchard, the ratios for X10, X30, and X50 were 22.08%, 25.19%, and 23.51%, respectively. In the cotton field, the ratios were 20.82% for M10, 40.55% for M30, and 55.90% for

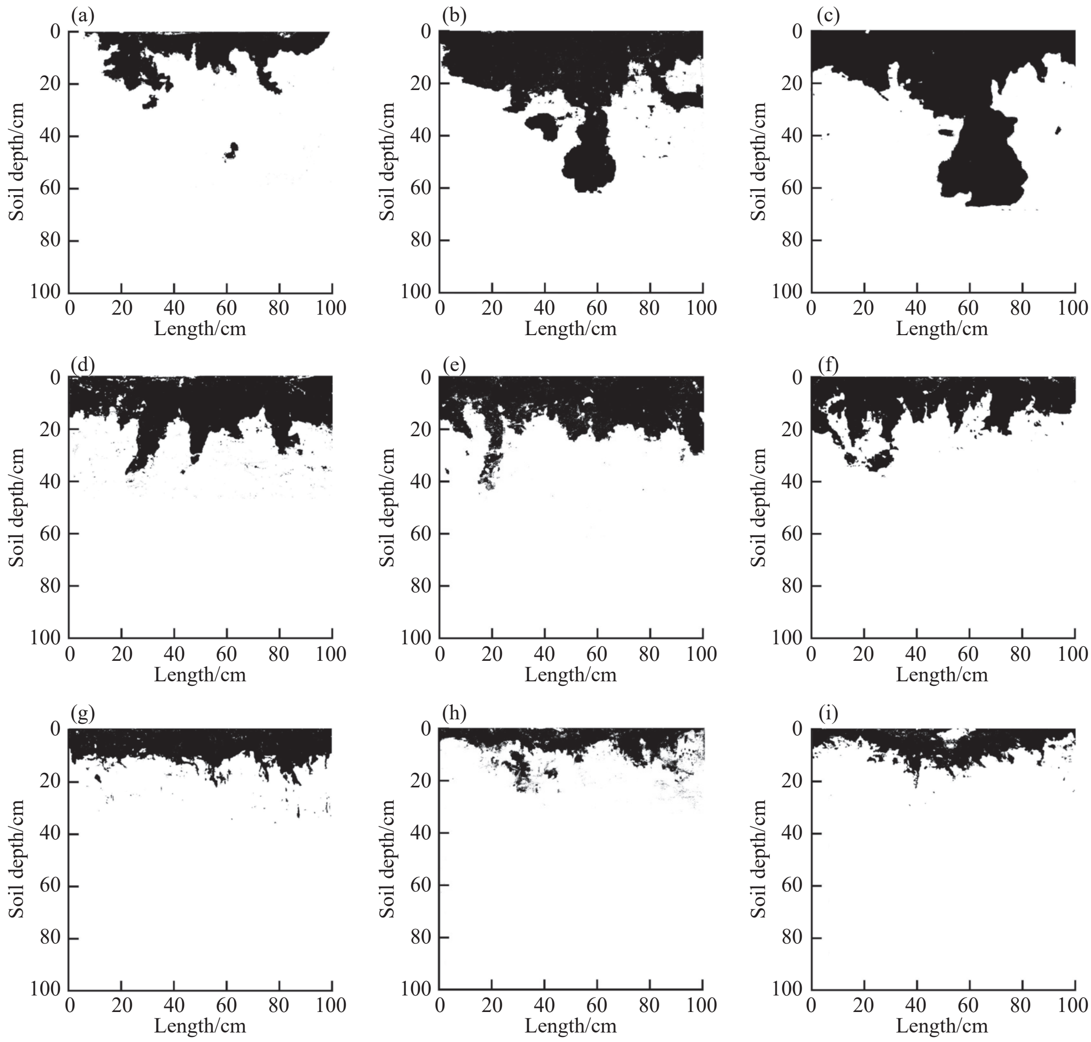

Fig. 4 Dye tracing soil profiles (a, L10; b, L30; c, L50; d, X10; e, X30; f, X50; g, M10; h, M30; i, M50)

M50. On average, the preferential flow ratios followed the order: Bare land (50.42%) > cotton field (30.09%) > pear orchard (23.59%). The relatively high variability and standard deviation in the cotton field indicate a more heterogeneous and complex soil pore structure, resulting in high preferential flow ratios compared to the pear orchard. Therefore, matrix flow was identified as the primary infiltration pathway in both the cotton field and pear orchard.

2.1.5 Length index

In the bare land, the length index values were 112.52% at L10, 170.28% at L30, and 174.70% at L50 as shown in Table 3. In the pear orchard, the values were 130.37% at X10, 129.25% at X30, and 131.42% at X50. For the cotton field, the values were 116.49% at M10, 100.18% at M30, and 90.12% at M50. The mean length index values for bare land, pear orchard, and cotton field were 152.50%, 130.35%, and 102.26%, respectively. These values indicate that preferential flow is most developed under the bare land condition as evidenced by the higher length index. In contrast, the lower values observed in the cotton field and pear orchard reflect more uniform and consistent matrix flow, suggesting that infiltration under the two land use conditions is predominantly controlled by matrix flow rather than preferential flow.

The length index shows significant negative correlations ($p<0.01$) with bulk density across all soil profiles under different land use types (Table 4). The correlation coefficients between the length index and sand content were 0.998 for the cotton field, 0.066 for the pear orchard, and 0.957 for the bare land. This indicates that sand content is not the primary factor controlling the development of preferential flow in the pear orchard. For clay content, the correlation coefficients were −0.512 in the bare land and −0.994 in the cotton field, indicating a negative relationship between clay content and preferential flow. However, in the pear orchard, clay content shows a positive correlation (0.462) with the length index. Silt content was negatively correlated with the length index across all soil profiles under these three land use types. This suggests that higher silt content consistently reduces the extent of preferential flow, regardless of land use types.

2.2 Estimation of recharge based on the CMB method

Fig. 5 shows the estimation of recharge and recharge coefficients under different land use conditions in the Kongque River Irrigation District. In bare land and unirrigated pear orchards (profiles L1, X1, and X2), recharge from rainfall alone ranged from 2.00 mm/a to 4.25 mm/a. In cotton fields utilizing drip irrigation, recharge values ranged from 23.47 mm/a to 59.16 mm/a, with a mean of 41.16 mm/a. Surface irrigated pear orchards showed higher recharge rates, ranging from 154.30 mm/a to 401.65 mm/a, with a mean of 264.48 mm/a.

The M1 profile, located the downstream of Kongque River, showed a recharge rate of 34.77 mm/a and a recharge coefficient of 17.83%. In contrast, profiles X5 and X9 exhibited significantly higher recharge rates of 357.49 mm/a and 202.55 mm/a, accompanied by recharge coefficients of 38.86% and 22.02%, respectively. In the upper reaches of the Kongque River, profiles M5 and M6 estimated recharge rates of 59.16 mm/a and 39.69 mm/a, with corresponding recharge coefficients of 30.34% and 20.35%. Further upstream in areas under pear cultivation areas, profiles X7, X12, X13, X14, and X18 exhibited high recharge rates of 332.81 mm/a, 285.92 mm/a, 207.81 mm/a, 367.27 mm/a, and 216.12 mm/a, with corresponding recharge coefficients of 36.18%, 31.08%, 22.59%, 39.92%, and 23.49%. Profiles M2, M3, M4, and M8 (cotton fields with drip irrigation) had recharge rates of 36.84 mm/a, 49.71 mm/a, 54.46 mm/a, and 38.41 mm/a, with recharge coefficients of 18.89%, 25.49%, 27.93%, and 19.69%. In the lower reaches, profiles X17 and X19, which represent pear orchards utilizing surface irrigation, exhibited estimated recharge rates of 231.76 mm/a and 246.18 mm/a, respectively, with corresponding recharge coefficients of 25.19% and 26.76%.

Fig. 6 shows the spatial distribution of recharge

Table 4 Pearson correlation between soil properties and length index

The length index of different land use types	Soil properties			
	Soil bulk density /g/cm^3	Sand /%	Clay /%	Silt /%
Bare land	−0.752**	0.957**	−0.512**	−0.900**
Cotton field	−0.998**	0.998**	−0.994**	−0.989**
Pear orchard	−0.985**	0.066	0.462	−0.298

Note: ** indicates significant correlation at p<0.01 level

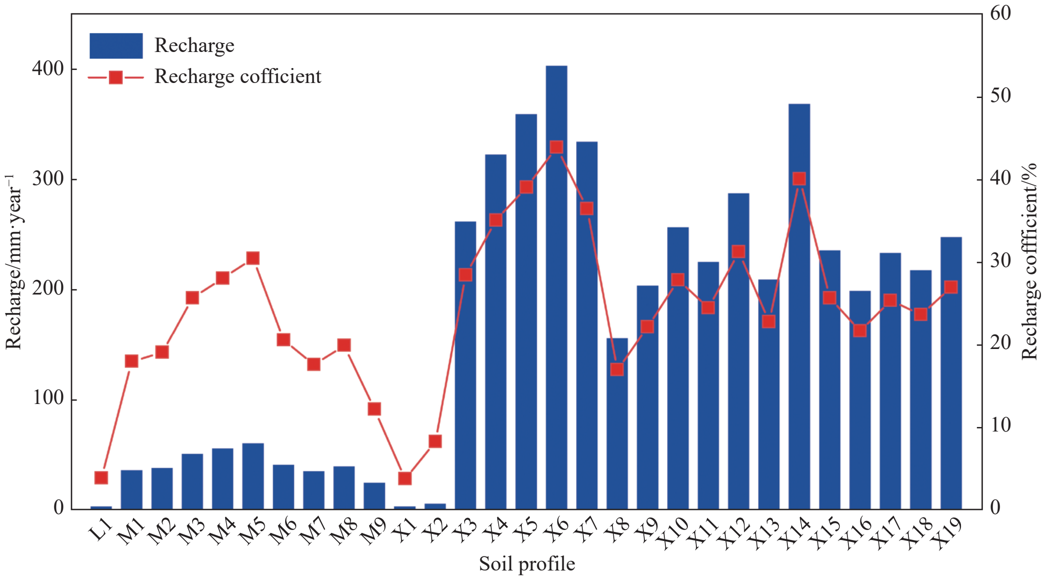

Fig. 5 Estimates of recharge and recharge coefficients under different soil profiles

coefficients determined by the empirical Bayesian Kriging method across the Kongque River Irrigation District. The highest recharge coefficients ranging from 0.28 to 0.33, were observed in the northeast region, where pear is the predominant economic crop (Fig. 2b). In contrast, the lowest recharge coefficients, between 0.13 and 0.16, were observed in the southwest, where primarily cultivated with cotton (Fig. 2b). Overall, the recharge coefficients gradually decrease from northeast to southwest, decreasing from 0.33 to 0.13.

3 Discussion

Factors influencing the infiltration process and recharge mainly include soil properties (Gong et al. 2021), rainfall intensity and duration, irrigation amount and method, as well as land use/cover (Zhang et al. 2021c). Our results clearly show that the infiltration rate was the lowest in the cotton field while the greatest infiltration depth occurred in the bare land (Fig. 4). This indicates that irrigated water percolates more effectively into deeper soil layers under bare land condition. A secondary peak in the stained area ratio at approximately 60 cm depth in the bare land is likely attributable to the presence of larger, well-connected pore spaces that facilitate preferential flow (Fig. 3a). This increased pore connectivity in the bare land promotes deeper infiltration and results in a larger stained area compared to the cotton field and pear orchard. In these cultivated areas, the limited number of macropores and denser soil structure restrict vertical water movement. These findings are consistent with the results from Zheng et al. (2018), who pointed out that higher sand content promotes preferential flow. As indicated in Table 1, the bare land contains the highest sand content (58.37%), whereas the cotton field exhibits the highest silt content (53.88%). This difference in soil texture may contribute to the reduced infiltration capacity observed in the cotton field. At the regional scale, the soil particle size becomes finer from the northeast to the southwest (Zhang, 2015), resulting in a decrease in infiltration capacity. Consequently, the northeast region shows higher recharge coefficients than the southwest region (Fig. 6). Furthermore, tillage practices play an important role in the infiltration process. Zhou et al. (2010) found that tillage can increase the soil porosity in the upper 0–10.00 cm but compact deeper soil layers in the cotton field, thereby impeding infiltration at greater depths. This phenomenon explains the shallowest observed infiltration depths and the reduced preferential flow development observed in the cotton field.

Additionally, the irrigation method significantly influences both infiltration rates and recharge. Surface irrigation is effective in pear orchards, as it can overcome the limitations imposed by fine-textured soils by promoting the downward movement of water through the soil profile, thereby enhancing recharge. In contrast, the drip irrigation method primarily meets the water requirements of cotton through direct root-zone delivery, which favors plant uptake and evapotranspiration while substantially reducing the available water for percolation and subsequent recharge. Consequently, the widespread adoption of the drip irrigation method could reduce long-term recharge in cotton fields, as pointed out by Porhemmat et al. (2018).

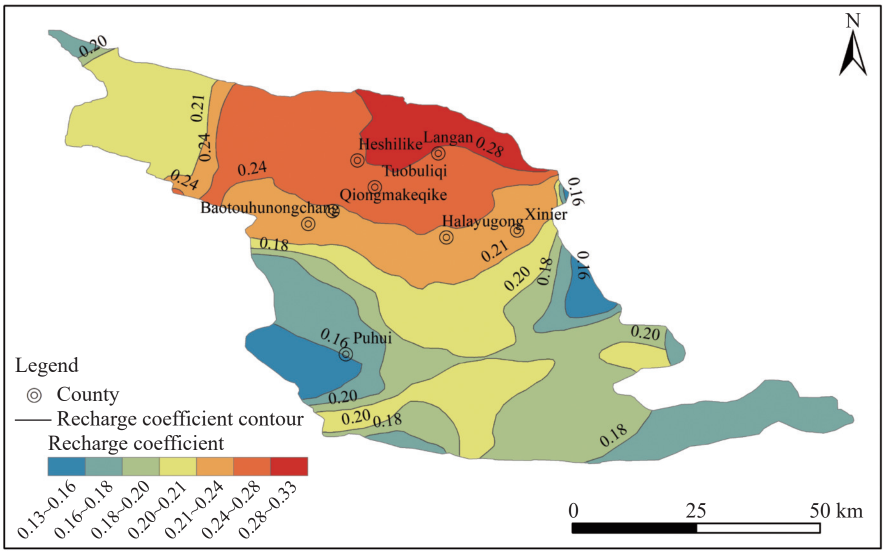

Fig. 6 The distribution of recharge coefficient in the Kongque River Irrigation District

The contour map of the groundwater level in the Kongque River Irrigation District shows a decreasing pattern from the northeast to the southwest (Figure from Zhang (2015)). In the middle and lower reaches, where cotton cultivation with drip irrigation predominated, the groundwater level was noticeably lower. This is primarily due to prolonged groundwater exploitation for irrigation and limited recharge in these areas. As mentioned above, tillage impeded deep infiltration, thereby contributing to the decline in groundwater levels. In contrast, in the upper reaches where pear orchards are irrigated using surface irrigation, this increases infiltration rates and slows down the rate of groundwater decline.

Although the CMB method is widely used to estimate groundwater recharge, it has several limitations. This method provides estimates at the point scale, applying it to the regional scale requires interpolation, which in turn increases the uncertainty associated with regional groundwater recharge estimations. Meanwhile, the CMB method relies on the assumption of a relatively steady-state system (Cook and Brunner, 2025; Cook et al. 1994). In this study, the estimation of chloride input from rainfall and dry deposition referenced from Zhang (2015) remains uncertain. To reduce the uncertainty in the groundwater recharge estimates, future research should focus on accurately quantifying chloride input fluxes, particularly from dry deposition and rainfall, which is a major source of uncertainty. Moreover, integrating multiple tracers and comprehensive analyses of soil properties is essential to verifying the matrix flow hypothesis (Yuan et al. 2015). Finally, if feasible, the implementation of multiple methods for estimating recharge is recommended in order to reduce the resulting uncertainty (Scanlon et al. 2002). These efforts will provide a more robust scientific basis for accurate quantification of recharge.

4 Conclusion

This study investigated the infiltration pathway under the bare land, cotton field, and pear orchard conditions through the dye tracer method and estimated recharge in the Kongque River Irrigation District employing the chloride mass balance method. Key factors influencing infiltration and recharge rates were identified. The major conclusions can be drawn as follows:

(1) Under the bare land condition, preferential flow predominantly occurs at depths of 18 cm to 70 cm, which can be attributed to the loose soil structure, high sand content, and the presence of large pore spaces between soil particles. Matrix flow servers as the primary infiltration pathway in both cotton field and pear orchard. This is mainly due to long-term tillage practices that result in deep soil compaction and a decreased number of macropores, thereby limiting the formation and progression of preferential flow.

(2) The recharge coefficient gradually decreased from northeast to southwest, ranging from 0.33 to 0.13. Drip irrigation in cotton fields resulted in a recharge of 23.47–59.16 mm/a (mean 41.16

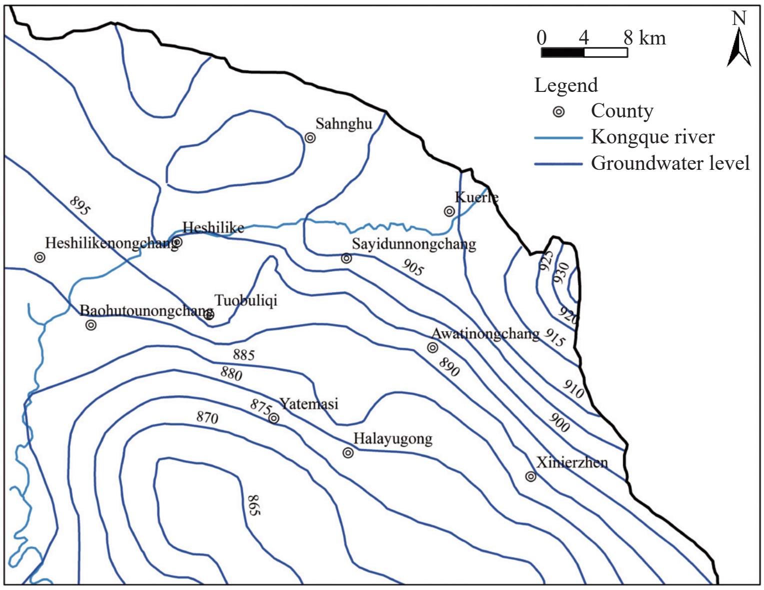

Fig. 7 Contour map of the groundwater level in the Kongque River Irrigation District (Figure from Zhang (2015))

mm/a), accounting for 21.11% of the total amount of irrigated water. In contrast, surface irrigation in pear orchards led to higher recharge, ranging from 154.30 mm/a to 401.65 mm/a (mean 264.48 mm/a), representing 28.75% of the total irrigation water.

Overall, this research provides a robust scientific basis for understanding the recharge process in irrigation areas, which is essential for sustainable water resource management and future agricultural planning.

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