Journal of Hydrology (2008) **356**, 209–222

available at www.sciencedirect.com

journal homepage: www.elsevier.com/locate/jhydrol

Estimating groundwater recharge in Hebei Plain, China under varying land use practices using tritium and bromide tracers

Bingguo Wang [a], Menggui Jin [a,*], John R. Nimmo [b], Lei Yang [a], Wenfeng Wang [a]

[a] *Key Laboratory of Biogeology and Environmental Geology, MOE; School of Environmental Studies, China University of Geosciences, 388 Lumolu, Wuhan 430074, China*
[b] *USGS, 345 Middlefield Road, Menlo Park, CA 94025, USA*

Received 2 February 2007; received in revised form 31 March 2008; accepted 4 April 2008

KEYWORDS
Applied tracer;
Tritium;
Bromide;
Groundwater recharge;
Hebei Plain

Summary Tritium and bromide were used as applied tracers to determine groundwater recharge in Hebei Plain, North China, to evaluate the impacts of different soil types, land use, irrigation, and crop cultivation practice on recharge. Additional objectives were to evaluate temporal variability of recharge and the effect on results of the particular tracer used. Thirty-nine profiles at representative locations were chosen for investigation. Average recharge rates and recharge coefficient determined by tritium and bromide tracing for different sites were 0.00–1.05 mm/d and 0.0–42.5%, respectively. The results showed relative recharge rates for the following paired influences (items within each pair are listed with the influence producing greater recharge first): flood-irrigated cropland and non-irrigated non-cultivation land, flood irrigation (0.42–0.58 mm/d) and sprinkling irrigation (0.17–0.23 mm/d), no stalk mulch (0.56–0.80 mm/d) and stalk mulch (0.44–0.60 mm/d), vegetable (e.g. Chinese cabbage and garlic, 0.70 mm/d) and wheat–maize (0.38 mm/d), peanut (0.51 mm/d) and peach (0.43 mm/d). The results also showed greater recharge for the first year of tracer travel than for the second. Because total precipitation and irrigation were greater in the first year than in the second, this may reflect temporal variability of recharge. The method may not be applicable where the water table is shallow (less than 3 m). A comparison of the near-ideal tritium tracer with the more common but less ideal bromide showed that bromide moved approximately 23% faster than tritiated water, perhaps because of anion exclusion.

---

[*] Corresponding author. Tel.: +86 27 67883461; fax: +86 27 87436235.
E-mail address: mgjin@cug.edu.cn (M. Jin).

0022-1694/$ - see front matter
doi:10.1016/j.jhydrol.2008.04.011

Introduction

In arid and semi-arid areas, where potential evapotranspiration equals or surpasses average precipitation, recharge is difficult to estimate (De Vries and Simmers, 2002; Sekhar et al., 2004). Hebei Plain, a semi-arid area, is one of the most important agricultural areas in China, but water shortages limit the local agricultural development. As is common in semi-arid regions, water resources are critical to economic development (De Vries and Simmers, 2002). Groundwater is the main source for the water supply, and agriculture uses approximately 70% of the total water supply. Water-saving irrigation has been practiced since the 1990s, strongly affecting the net groundwater recharge (Jin et al., 1999). Therefore, accurate estimation of the current rate of groundwater recharge is essential for efficient and sustainable groundwater management in the semi-arid region.

Groundwater recharge may be estimated by several conventional methods such as the water-balance, Darcian approach, lysimeter, water table fluctuation, and numerical simulation methods (Simmers, 1997; Scanlon et al., 2002; Nimmo et al., 2005). Most of these methods require analysis of a large volume of hydrological data (precipitation, surface runoff, evapotranspiration, change in groundwater storage, etc.) accumulated over a considerable time span, which is inadequate or unreliable in many areas (Chand et al., 2004). An advantage of tracer techniques for recharge estimation (Zimmermann et al., 1966, 1967; Dincer et al., 1974; Athavale et al., 1980; Athavale and Rangarajan, 1988; Wood and Sanford, 1995; Sukhija et al., 1996; Rangarajan and Athavale, 2000; Chand et al., 2004) is that the requirements are often for shorter-term and more easily obtained data. Three categories of tracer methods are historical tracers, environmental tracers, and applied tracers (Edson, 1998).

Historical tracers result from human activities or events such as contaminant spills (e.g. Nativ et al., 1995) and atmospheric nuclear testing (^{3}H and ^{36}Cl). These historical tracers or event markers can estimate recharge rates, mainly over the past 50 years (Allison and Hughes, 1978, 1983; Allison et al., 1994; Scanlon, 1992, 2000; Cook et al., 1994; Lin and Wei, 2006). Industrial and agricultural sources produce contaminants such as bromide, nitrate, atrazine, and arsenic, and these can provide qualitative evidence for recent recharge; however, uncertainties with respect to source location, concentration, timing of contamination, and possible non-conservative contaminant behavior sometimes make it difficult to quantify recharge.

Environmental tracers such as chloride (Cl) are supplied naturally to the land surface through the Earth's atmosphere. With an understanding of how they accumulate and travel in the subsurface, they can be used to estimate natural recharge rates (Phillips, 1994; Scanlon, 2000).

Applied tracers usually are selected chemicals or isotopes that are naturally present only in at low concentrations, applied at the soil surface or injected at some depth. Unsaturated-zone water transports the tracer downward and the depth of the tracer front indicates an average transport velocity that may indicate a recharge rate. Common tracers include bromide (Jury et al., 1982; Rice et al., 1986; Sharma et al., 1987; Hendrickx et al., 1993), ^{3}H (Saxena and Dressie, 1984; Athavale and Rangarajan, 1988; Jin et al., 2000a; Rangarajan et al., 2005), and visible dyes (Kung, 1990; Flury et al., 1994; Forrer et al., 1999).

For recharge estimation the use of historical or environmental tracers is far more common than the use of applied tracers. With applied tracers, the investigator has control over the timing, placement, and amount of tracer, which can be important advantages. For example, the tracer does not necessarily have to be applied at the land surface. Injection of the tracer at depth avoids the complexities of the upper unsaturated zone (effects of roots, numerous preferential flow channels, and cultural disturbances), which cause considerable uncertainty in recharge estimates obtained using natural or environmental tracers. Other advantages come from the fact that various substances are available to be chosen for use as a tracer. Our study, for example, provides an opportunity for field-comparison of recharge rates, the near-ideal tritium tracer with the more common but less ideal bromide. Disadvantages of applied tracer methods include additional cost to apply tracers, time required between application and sampling, and possible difficulty in finding the optimal location to sample.

The main objectives of this study are to evaluate the influence of different soil types, land use, irrigation, and crop cultivation practice on recharge in Hebei Plain, North China. Additional objectives are to evaluate temporal variability of recharge and the effect on results of the particular tracer used.

Background of the research area

Hebei Plain, adjacent to Beijing and Tianjin municipalities, is part of the North China Plain. The southern boundary is Henan province and the eastern boundary is Bohai Bay of the Pacific Ocean (Fig. 1). The total area of Hebei Plain is 73,000 km^{2}, 40,000 km^{2} of which is cultivated land. The population totals 50 million. The Plain has very flat topography, deep soil, and abundant sunshine, and is one of the most important agricultural areas in China. Because of monsoonal influences, rainfall and runoff are highly variable, with 60—70% of the annual precipitation (500—600 mm) and runoff concentrated between June and August. This variability produces a spectrum of natural disasters such as spring droughts, autumn floods, soil salinization and alkalization, and saline groundwater, all of which limit the development of agriculture in the area. In addition, with increased intensity of agriculture since the 1980s, groundwater over-extraction has led to a reduction of volume of fresh unconfined groundwater and continued lowering of piezometric levels of deep fresh confined water. These developments have resulted in serious environmental problems such as seawater intrusion, saline connate water invasion into fresh groundwater, and land subsidence. Consequently, socio-economic and agricultural impacts of water shortages and environmental degradation are increasing in severity (Jin et al., 1999).

In this region, the key issue for agricultural development is to develop and manage the limited water resources in such a way that they can be used on a sustainable basis. Current water-saving agricultural practices in the area certainly

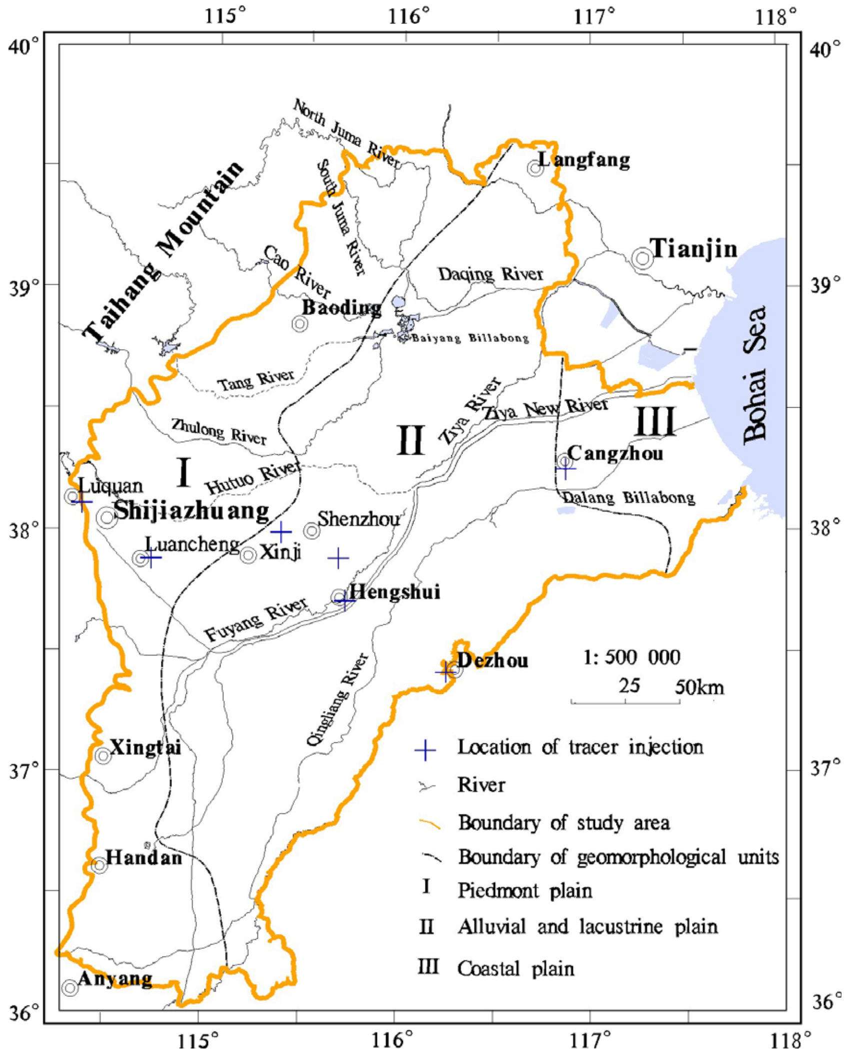

Figure 1 Map of Hebei Plain and locations of tracer injecting.

influence the soil moisture regime and recharge processes and are directly reflected by differences in net groundwater recharge (Jin et al., 1998, 2000b).

According to the hydrogeologic conditions and the character of the groundwater system, representative zones from the piedmont to coastal plain were selected for particular research. They are (1) the Luquan (LQ) and Luancheng (LC) representative zone on the piedmont plain; (2) the Xinji (XJ), Shenzhou (SZ), Hengshui (HS) and Dezhou (DZ) representative zone on the alluvial and lacustrine plain; and (3)

Table 1 General features of the representative zones

Geomorphologic setting	Representative zone (code)	Location	Water table depth (m)	Lithology	Mean annual rainfall (mm/yr)
Alluvial and pluvial plain	Luquan (LQ)	Huolu, Luquan county	10–15	Silt clay and silt	547
	Luancheng (LC)	Niejiazhuang, Luancheng county	30–35	Clay and silt clay	537
Alluvial and lacustrine plain	Xinji (XJ)	Jiucheng, Xinji county	25–30	Silt	520
	Shenzhou (SZ)	Hujiachi, Shenzhou county	10–15	Clay and silt clay	511
	Hengshui (HS)	Experimental ground of agriculture, Taocheng region	1–3	Clay and silt clay	511
	Dezhou (DZ)	Village of Dongbali, Chenzhuang town	1–4	Silt clay	522
		Village of Guojia'an, Songguantun town	1–4	Silt	522
Alluvial and coastal plain	Cangzhou (CZ)	Xiaozhaozhuang, Cangzhou county	1–4	Silt	554

the Cangzhou (CZ) representative zone on the coastal plain (Fig. 1). General features of the representative zones are listed in Table 1.

Principles and methods

The procedure for determining groundwater recharge by applied tracers (Jin et al., 2000a,b) is put in tracers at a known depth, collect samples and monitor tracer concentration changes in profiles, calculate the vertical percolating velocity (v, cm/d) of soil water by observing the downward movement (Δz) of the tracer peaks, then calculate groundwater recharge rate (Rr, mm/d) from

$$Rr = 10v\theta = 10\theta\Delta z/\Delta t \quad (1)$$

where Δt is the time interval between tracer injecting and sampling (d); and θ is the average soil water content (–) within the depth interval Δz (cm) during Δt.

Recharge coefficient (Rc) is the fraction of the precipitation or irrigation entering into the groundwater over the specific time interval and its formula is

$$Rc = Rr * \Delta t/(P + I) * 100\% \quad (2)$$

where Rr is recharge rate (mm/d); P is precipitation during Δt, mm; and I is irrigation during Δt, mm.

At each site locations were selected for tracer application and sampling. Thirty-nine sites represented different

Table 2 Summary of tritium and bromide tracing sites

Number	Lithology	Tracers	Land use	Injection date	Sampling date	Memo
LQ01	Silt clay and silt	^{3}H	Maize–wheat	03-8-17	05-9-24	Flood irrigation
LQ02		^{3}H	Maize	03-8-17	04-9-27	Flood irrigation
LQ03		^{3}H	Non-cultivation	03-8-17	04-9-27	Non-irrigation
LQ71		^{3}H and Br$^-$	Apple	03-11-8	04-9-26	Flood irrigation
LQ72		^{3}H and Br$^-$	Grape	03-11-8	04-9-26	Flood irrigation
LQ73		^{3}H	Wheat–maize	03-11-8	04-9-26	Flood irrigation
LC05	Clay and silt clay	^{3}H and Br$^-$	Wheat–maize	03-8-20	04-9-28	Sprinkling irrigation
LC06		^{3}H and Br$^-$	Wheat–maize	03-8-20	05-9-22	Sprinkling irrigation
LC07		^{3}H and Br$^-$	Wheat–maize	03-8-20	04-9-28	Flood irrigation
LC08		^{3}H and Br$^-$	Wheat–maize	03-8-20	05-9-22	Flood irrigation
LC10		^{3}H and Br$^-$	Non-cultivation	03-8-20	04-9-29	Non-irrigation
LC81		^{3}H and Br$^-$	Non-cultivation	03-11-9	05-9-22	Non-irrigation
LC82		^{3}H and Br$^-$	Wheat–maize	03-11-9	04-9-28	Stalk mulch
LC84		^{3}H and Br$^-$	Wheat–maize	03-11-9	04-9-28	No stalk mulch
LC83		^{3}H and Br$^-$	Wheat–maize	03-11-9	05-9-23	Stalk mulch
LC85		^{3}H and Br$^-$	Wheat–maize	03-11-9	05-9-23	No stalk mulch
LC88		Br$^-$	Wheat–maize	04-5-25	05-9-22	Non-fertilizer
HS19	Clay and silt clay	^{3}H	Non-cultivation	03-8-24	04-9-25	Non-irrigation
HS21		^{3}H	Maize	03-8-24	04-9-25	Flood irrigation
HS23		^{3}H	Wheat–maize	03-11-3	04-9-25	Organic fertilizer
HS25		^{3}H	Wheat–maize	03-11-3	04-9-25	Compound fertilizer
HS27		^{3}H	Wheat–maize	03-11-3	04-9-25	Chemical fertilizer
XJ00	Silt	Br$^-$	Peanut	04-5-27	05-9-25	Flood irrigation
XJ02		Br$^-$	Peach	04-5-27	05-9-25	Flood irrigation
SZ51	Clay and silt clay	Br$^-$	Wheat–maize	04-5-27	05-9-26	Flood irrigation
SZ52		Br$^-$	Non-cultivation	04-5-27	05-9-26	Non-irrigation
DZ16	Silt clay	^{3}H and Br$^-$	Non-cultivation	03-8-23	04-9-23	Non-irrigation
DZ17		^{3}H and Br$^-$	Maize–cotton	03-8-23	04-9-23	Flood irrigation
DZ18		^{3}H and Br$^-$	Maize–cotton	03-8-23	05-9-27	Flood irrigation
DZ41	Silt	^{3}H	Cotton	03-11-5	04-9-23	Non-irrigation
DZ42		^{3}H	Apple	03-11-5	04-9-23	Flood irrigation
DZ43		^{3}H	Wheat–maize	03-11-5	04-9-23	Flood irrigation
CZ11	Silt	^{3}H	Non-cultivation	03-8-22	04-9-21	Non-irrigation
CZ12		^{3}H	Non-cultivation	03-8-22	05-9-28	Non-irrigation
CZ13		^{3}H	Wheat–maize	03-8-22	04-9-21	Flood irrigation
CZ14		^{3}H	Wheat–maize	03-8-22	05-9-28	Flood irrigation
CZ65		Br$^-$	Non-cultivation	04-5-20	05-9-28	Non-irrigation
CZ66		Br$^-$	Vegetable	04-5-20	05-9-28	Flood irrigation
CZ68		Br$^-$	Wheat–maize	04-5-20	05-9-28	Flood irrigation

types of soil, land use, irrigation and crop cultivation practice (Table 2 and Fig. 2). Tritium and bromide were injected on August 17—24 and November 3—11, 2003 and sampled on September 21—29, 2004 and September 22—28, 2005.

At each test location three holes (2 cm in diameter and 100 cm deep) were drilled with a hand auger for tritium injecting at the vertices of a 10-cm equilateral triangle. A 30 ml volume of tritium solution was injected at the holes though a conduit. At the centre of the triangle or at some sites separately, a hole (5 cm in diameter) was drilled to put in 100—200 g NaBr (as the bromide tracer) at a specific depth (XJ00, XJ02 and CZ65 60 cm; SZ51, SZ52, CZ66, CZ68 70 cm; and others 100 cm) A PVC tube was also buried in this hole to 40 cm depth to mark the location for later sampling.

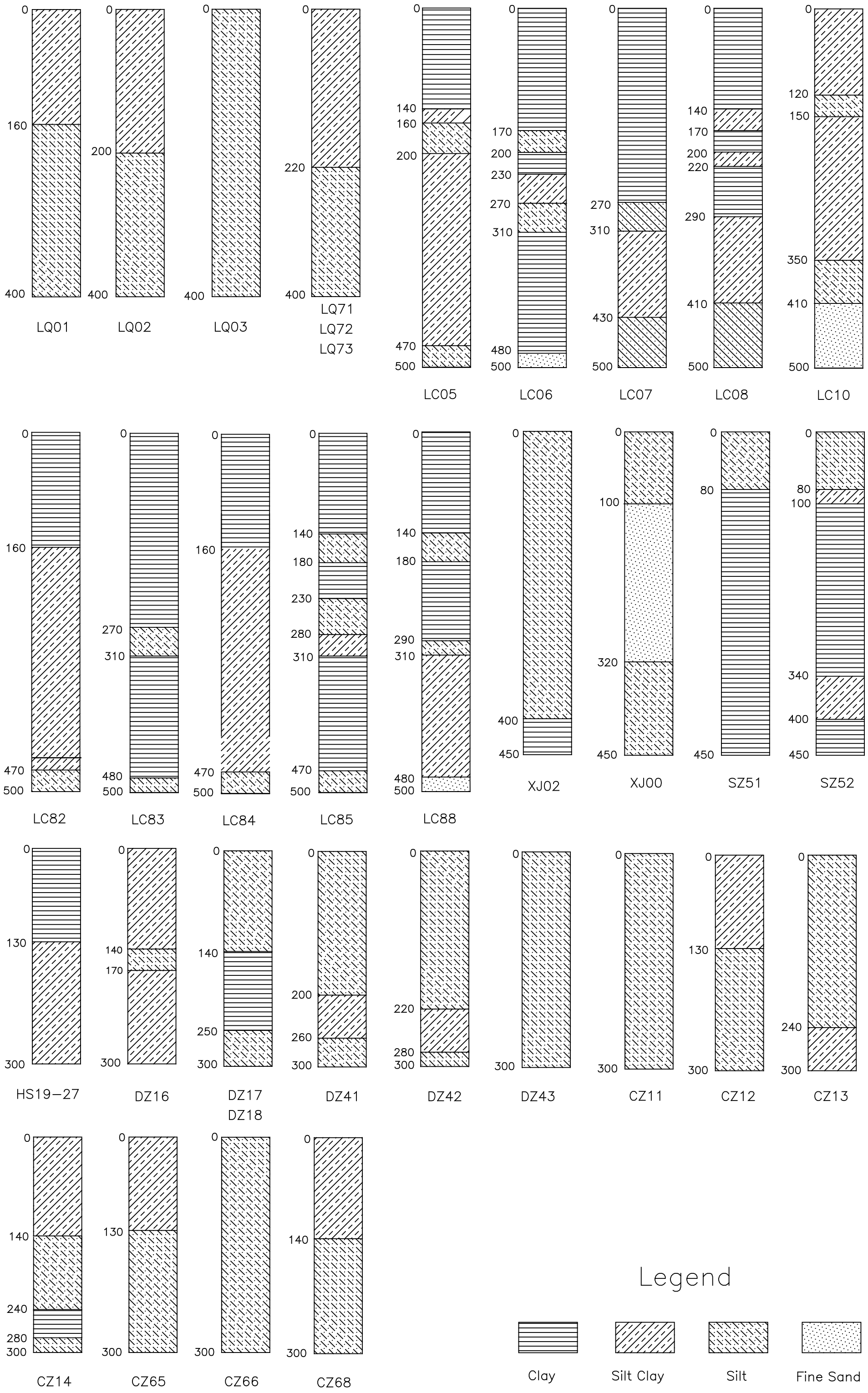

Figure 2 Soil profile textures of tracing sites.

At the designated time, soil core samples were taken at the centre of the triangle from 1.0 m depth to the water table (or to 5.0 m in cases where the water table was deeper than that). The sampling depth intervals were 10 cm from 1.0 m to 2.0 m and 20 cm below 2.0 m. Each soil sample of about 200 g was stored in a plastic bag to minimize evaporation. As soon as the samples arrived in the laboratory, soil water was extracted into a flask by oil bath distillation at 130 °C. The tracer content of the water samples was measured by liquid scintillation analyzer (model: Tri-Carb 3170 TR/SL) in Nanjing University.

The soil samples for bromide analysis were taken at the same time as those for tritium. The samples were air-dried, triturated, and filtered by 1 mm sizer. Thereafter, 500 ml of deionised water was added to 50 g of filtered sample and shaken for 2 h. The mixture was allowed to settle for 24 h. The resulting solution was filtered through a 0.45 μm Millipore membrane filter and stored in a 596 ml polyethylene bottle until analysis by an ion electrode method (Model: PBr-1, 217 made by Shanghai Precision & Scientific Instrument Co., Ltd). The measurement uncertainty ranged from 6.6% to 10% (Wang et al., 2004).

Results and discussion

The downward movement of tracer peaks was determined by the shape of the curve from the profiles, the largest value of tracer content. Almost all profiles of tritium and bromide (Figs. 3–7) indicate clear single peaks rather than multiple ones (only a few bromide profiles, such as LC08 and LC84, showing in non-obvious multiple peaks shape). Measurement uncertainty in the vertical direction is 5–10 cm (a half of vertical sampling interval).

Table 3 summarizes vertical percolating velocity, precipitation, irrigation, recharge rates, recharge coefficient, and other related information. The results show the average recharge rates determined by tritium and bromide tracing for the different sites ranged from 0.00 to 1.05 mm/d, with a mean of 0.35 mm/d (Fig. 8). By statistical analysing, the coefficient of variation of the average recharge rates (*Rr*) and precipitation and irrigation (*P* + *I*) are 0.70 and 0.41,

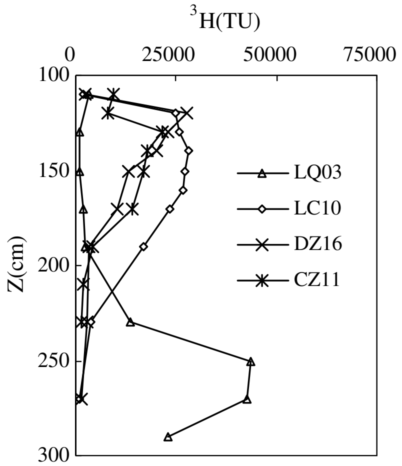

Figure 3 Tritium profiles for non-cultivated land with no irrigation in representative zones.

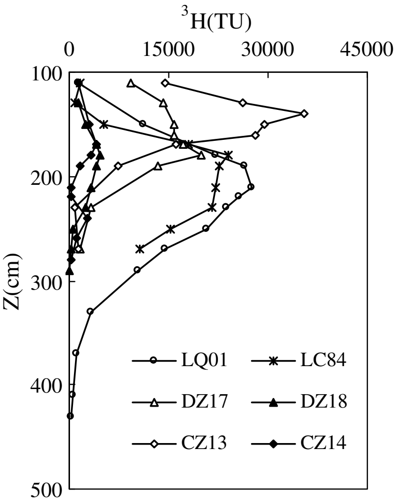

Figure 4 Tritium profiles for cropland with flood irrigation in representative zones.

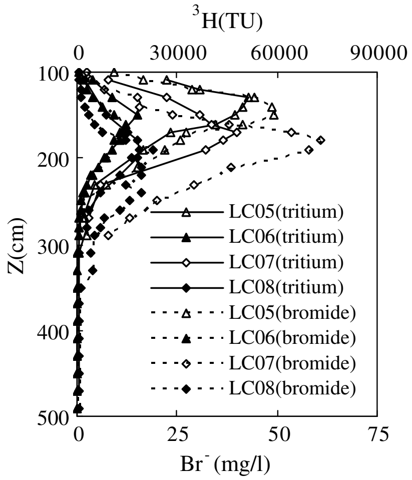

Figure 5 Tritium and bromide profiles for wheat–maize with sprinkling (LC05, LC06) and flood (LC07, LC08) irrigation.

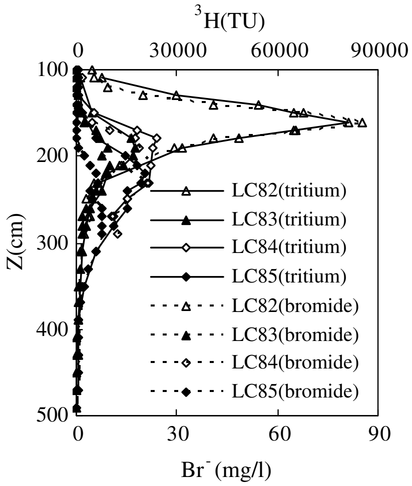

Figure 6 Tritium and bromide profiles for wheat–maize with (LC82, LC83) and without (LC84, LC85) stalk mulch.

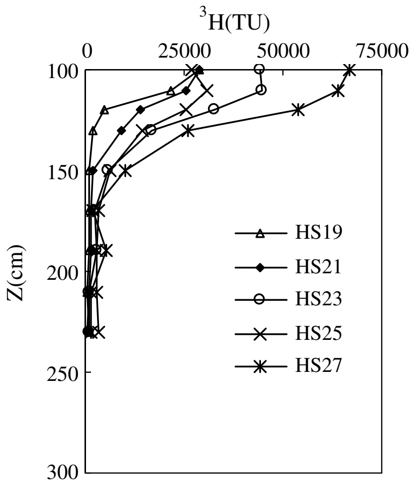

Figure 7 Tritium profiles for non-cultivation (HS19), maize (HS21), wheat–maize with organic fertilizer (HS23), compound fertilizer (HS25), and chemical fertilizer (HS27) in Hengshui.

respectively (Table 4), which also indicate *Rr* exhibits the higher spatial variability than *P* + *I*. The demonstrated variability of the recharge rate reflects the influence of different crops, cultivation practices, irrigation regimes, and soil types.

Cover treatment

Comparison in paired locations having nearly the same dates of injecting and sampling shows that generally there is greater recharge in flood-irrigated cropland than in non-irrigated non-cultivated land (Fig. 9). Unusually high recharge estimates for sites LQ03 and SZ52 result from LQ03 being located in a depression and inundated, and SZ52 being flooded by well-drilling slurry.

Irrigation regime

At Luancheng there were directly comparable locations representing three different irrigation regimes: flood-irrigated cropland (LC07, LC08), sprinkler-irrigated cropland (LC05, LC06), and non-irrigated non-cultivated land (LC10). Comparison shows that sprinkler irrigation reduced recharge compared to flood irrigation. The results also show that recharge rates for non-irrigated non-cultivated land were greater than for sprinkler-irrigated cropland (Fig. 10A), probably because transpiration was greater for cropland under the water-saving irrigation practice than it was for the less-vegetated non-irrigated non-cultivated land.

The implications include: while less water applied for irrigation, groundwater recharge (esp irrigation return flow) and soil evaporation will be reduced; and water saving irrigation practice should pay more attention to reduce soil evaporation for increasing water use efficiency.

Straw mulch

Adjacent blocks with and without straw mulch were selected in Luancheng. These blocks have almost the same lithology, crop (winter wheat, seeding on the middle October and summer maize seeding in early June), and irrigation regime (flood irrigation, equal in amount and time). One block differs in having been mulched with about 4500 kg/ha of decomposed maize-stalk in early November. Table 5 and Fig. 10B summarize the results of tritium tracing in Luancheng. Comparison shows the blocks with no straw mulch (LC84 and LC85, averaging 0.68 mm/d) have higher recharge rates than those with straw mulch (LC82 and LC83, averaging 0.52 mm/d). Straw mulch may have reduced recharge probably because it reduced rain infiltration to soil and it led to increased crop growth, resulting in increased transpiration. Total rainfall was 1135 mm in Luancheng during the two-year experiment. But rainfall that fell in storms of less than 10 mm totaled 293.4 mm. This rain from small storms may be more easily intercepted by the plant canopy and straw, thereby reducing rain infiltration to soil. On the other hand, straw mulch may improve soil physical properties, increase nutrients, enhance the activity of soil microbes, regulate soil temperature, and reduce soil evaporation (Shen et al., 1998), all of which can promote crop growth and increase crop transpiration. Maybe also because it damped out sudden fluctuations in rainfall intensity. Short burst of high-intensity rain might lead to greater preferential flow and therefore greater recharge, in soil without mulch.

Land use

Different land use resulted in different recharge rates. Conditions of XJ00 (peanut) and XJ02 (peach) were almost similar but with different crops. The recharge rate for peanut (0.51 mm/d) was larger than for peach (0.43 mm/d) (Fig. 11A). This may result from the fact that peach has deep roots and consumes more soil water than peanut. The recharge rate for vegetable (e.g. Chinese cabbage and garlic) was larger than for wheat–maize (cf. CZ66 0.70 mm/d and CZ68 0.38 mm/d) (Fig. 11B) because vegetable was irrigated with more water (1070 mm) than wheat–maize (270 mm).

Soil types

There were almost similar water table depth, land use (non-cultivation) and non-irrigation but different lithology for sites CZ11 (silt), DZ16 (silt clay) and DZ41 (silt), see Fig. 2. The recharge rate in DZ16 (0.15 mm/d) was lower than the other two (DZ41, 0.46 mm/d; CZ11, 0.27 mm/d), supporting the generalization that coarse soil results in more groundwater recharge.

Relationship between groundwater recharge and precipitation and irrigation (*P* + *I*)

The effects of precipitation or irrigation on the recharge were also quantificationally analyzed in this region. According to the average result of tritium and bromide tracing (excluding LQ03, SZ52, LQ71 and LQ72), a linear relationship between groundwater recharge and precipitation and irrigation with a correlation coefficient of 0.74 (significant at the 0.01 level), is shown in Fig. 12. The linear relationship by least-squares fitting is

Table 3 Summary of recharge determined by tritium and bromine tracing

Number	ΔZ (cm)		θ (%)	Δt (d)	v (cm/d)		P (mm)	I (mm)	Rr (mm/d)		Rc (%)	
	^{3}H	Br$^-$			^{3}H	Br$^-$			^{3}H	Br$^-$	^{3}H	Br$^-$
LQ01	110	–	33.3	769	0.14	–	1135	450	0.48	–	24.4	
LQ02	50	–	33.3	407	0.12	–	814	75	0.41	–	18.8	–
LQ03	150	–	26.4	407	0.37	–	814	0	0.97	–	48.5	–
LQ71	110	110	31.5	323	0.34	0.34	538	150	1.07	1.07	50.2	50.2
LQ72	150	230	30.7	323	0.46	0.71	538	150	1.42	2.18	66.7	102.3
LQ73	50	–	31.7	323	0.15		538	225	0.49	–	20.7	–
LC05	30	40	30.7	405	0.07	0.10	702	158	0.23	0.30	10.8	14.1
LC06	50	60	25.7	764	0.07	0.08	1135	458	0.17	0.20	8.2	9.6
LC07	70	80	33.8	405	0.17	0.20	702	300	0.58	0.67	23.5	27.1
LC08	90	90	35.7	764	0.12	0.12	1135	675	0.42	0.42	17.7	17.7
LC10	40	60	33.0	406	0.10	0.15	702	0	0.32	0.49	18.5	28.4
LC81	50	50	29.6	683	0.07	0.07	934	0	0.22	0.22	16.1	16.1
LC82	60	60	32.2	324	0.19	0.19	501	300	0.60	0.60	24.3	24.3
LC83	90	110	33.2	684	0.13	0.16	934	675	0.44	0.53	32.4	52.6
LC84	80	130	32.5	324	0.25	0.40	501	300	0.80	1.30	18.7	22.5
LC85	120	190	32.1	684	0.18	0.28	934	675	0.56	0.89	23.8	37.8
LC88	–	75	29.8	485	–	0.15	833	300	–	0.46	–	19.7
XJ00	–	168	14.9	486	–	0.35	890	600	–	0.51	–	16.6
XJ02	–	142	14.8	486	–	0.29	890	600	–	0.43	–	14.0
SZ51	–	47	37.2	487	–	0.10	890	375	–	0.36	–	13.9
SZ52	–	50	39.1	487	–	0.10	890	0	–	0.40	–	21.9
HS19	0	–	28.4	398	0.00	–	593	0	0	–	–	–
HS21	0	–	34.1	398	0.00	–	593	0	0	–	–	–
HS23	10	–	34.7	327	0.03	0.00	379	225	0.11	0	–	–
HS25	10	–	34.3	327	0.03	0.00	379	225	0.10	0	–	–
HS27	0	–	32.0	327	0.00	–	379	225	0	–	–	–
DZ16	20	20	30.4	397	0.05	0.05	723	0	0.15	0.15	8.2	8.2
DZ17	80	80	32.2	397	0.20	0.20	723	90	0.65	0.65	32.4	32.4
DZ18	80	110	35.0	766	0.10	0.14	1333	90	0.37	0.50	18.2	24.6
DZ41	50	–	29.7	323	0.15	–	455	0	0.46	–	32.6	–
DZ42	0	–	26.6	323	0.00	–	455	75	0	–	–	–
DZ43	0	–	30.8	323	0.00	–	455	225	0	–	–	–
CZ11	30	–	35.3	396	0.08	–	758	0	0.27	–	14.1	–
CZ12	50	–	37.2	768	0.07	–	1357	0	0.24	–	13.6	–
CZ13	40	–	30.5	396	0.10	–	758	150	0.31	–	13.3	–
CZ14	70	–	31.9	768	0.09	–	1357	450	0.29	–	13.1	–
CZ65	–	30	34.5	496	–	0.06	910	0	–	0.21	–	11.4
CZ66	–	105	33.1	496	–	0.21	910	1070	–	0.70	–	17.5
CZ68	–	57	32.9	496	–	0.11	910	270	–	0.38	–	17.4

Notes: P: precipitation; I: irrigation; Rc: recharge coefficient and its formula is $Rr * \Delta t/(P + I) * 100\%$; LQ03, LQ71 and LQ72 was located in a depression and inundated; SZ52 was flooded by well-drilling slurry.

$$R = 0.21(P + I) - 47.75 \qquad (3)$$

where R is groundwater recharge (mm), P is precipitation (mm) and I is irrigation (mm) over the time interval considered.

Spatial variability of recharge coefficients (*Rc*)

The recharge coefficients (*Rc*) were used to analyze the spatial variability of recharge (the right column of Table 3). Fig. 8 reflects the spatial variability of the recharge coefficients (excluding LQ03, LQ71, LQ72 and SZ52). It shows average *Rc* determined by tritium and bromide tracing for different sites varied from 0.0% to 42.5%. For flood-irrigated cropland, *Rc* in DZ is the highest, then LC, LQ, SZ, and CZ is the lowest (Fig. 13A). But for non-irrigated non-cultivation land, *Rc* in SZ is the highest, then LC, CZ, and DZ is the lowest (Fig. 13B).

For Luancheng representative zone, *Rc*s change with the irrigation regimes and cultivation practices. From Fig. 14

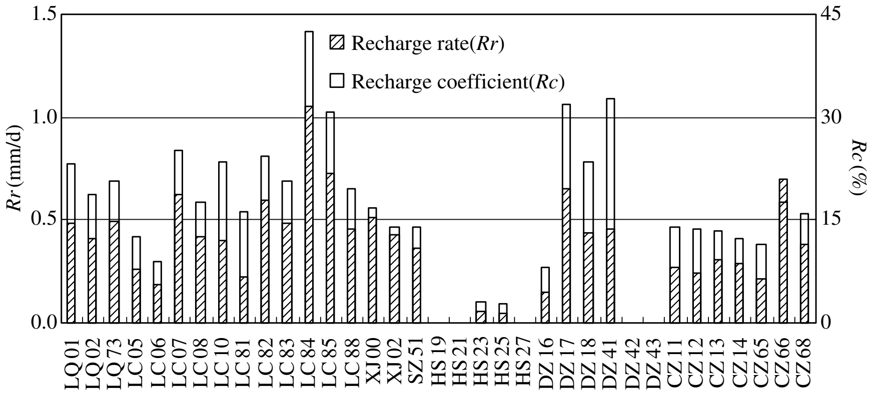

Figure 8 Average recharge rates (*Rr*) and recharge coefficient (*Rc*) determined by tritium and bromide tracing for different sites.

Table 4 Statistic of the recharge rate (*Rr*) and precipitation and irrigation (*P* + *I*)

Statistic	*Rr* (mm/d)	*P* + *I* (mm)
Mean	0.35	1053
SD	0.24	433
CV	0.70	0.41

SD, standard deviation; CV, coefficient of variation (SD/mean).

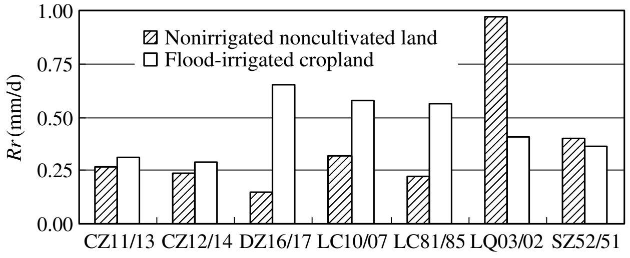

Figure 9 Recharge rates (*Rr*) of different cover treatment in different representative zones. Note: Recharge rates for sites SZ51and SZ52 determined by bromide tracing, others by tritium tracing.

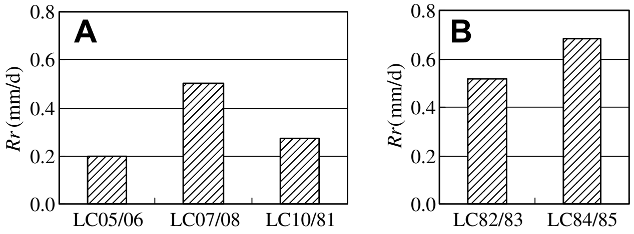

Figure 10 Averaged recharge rates (*Rr*) under different irrigation and stalk mulch treatments for wheat—maize fields in Luancheng. (A) Comparison of irrigation regime: LC05/06 sprinkling irrigation; LC07/08 flood irrigation; LC10/81 non-irrigated non-cultivation land. (B) Comparison of stalk mulch and no mulch: LC82/83 stalk mulch with flood irrigation; LC84/85 no stalk mulch with flood irrigation.

and Table 5 we can see: the *Rc* for wheat—maize fields with no stalk mulch is higher than that with stalk mulch, and the *Rc* for wheat—maize fields with sprinkling irrigation is lower than that for cropland with flood irrigation and for non-cultivated land with non-irrigation.

Temporal variability of recharge rate

To compare recharge rates between the first year and the second year at the same site, the second year recharge rate (R_{2nd}) was determined from

$$R_{2nd} = (R_{all} * \Delta t_{all} - R_{1st} * \Delta t_1)/\Delta t_2 \qquad (4)$$

where R_{all} is the recharge rate for the two-year period, Δt_{all} (d) is the duration of the two-year test; Δt_1 is the duration of the first year test, and $\Delta t_2 = t_{all} - \Delta t_1$. All units for R_{all}, R_{1st} and R_{2nd} are in mm/d and *t* are in days. The recharge rates for the first year, the second year and the two-year period are summarized in Table 6. Comparing at the same site (at sites such as LC05 and LC06, LC07 and LC08, LC82 and LC83, LC84 and LC85, DZ17 and DZ18, CZ11 and CZ12, CZ13 and CZ14), the recharge rate for the first year (between 0.23 and 1.30 mm/d) was greater than for the second year (0.07—0.52 mm/d). A major reason may be that total precipitation and irrigation per day of the first year was greater than that of the second year (Table 6), reflecting temporal variability of recharge rate. This result may also reflect a greater tracer-transport speed early in the first year, perhaps in response to the initial injection. Another possibility might be that the transport speed, independent of the actual recharge rate, may be greater at shallower depths, where there likely is more influence of roots and macropores (Tyler and Walker, 1994).

Discussions of the method

The results also indicate that for some representative zones such as Hengshui and Dezhou the method may be not applicable due to a shallow water table (ranging from 1 to 3 m). The tracer peaks (Fig. 7 and Table 3) remained almost stable near 1 m depth (to at most 1.5 m depth for DZ41) at those locations, suggesting almost no recharge during the test. This contradicts the likelihood that there is significant recharge from the total infiltration of about 600 mm (including irrigation) during the test. On the other hand, the average

Table 5 Recharge rates and *Rc* determined by tritium tracing in Luancheng (LC)

Item	Number	Land use	Date of injecting	Date of sampling	*P* (mm)	*I* (mm)	*Rr* (mm/d)		*Rc* (%) = *Rr*/(*P* + *I*)	
							^{3}H	Avg.	^{3}H	Avg.
Sprinkling irrigation	LC05	Wheat–maize	03-8-20	04-9-28	702	158	0.23	0.20	10.8	9.5
	LC06	Wheat–maize	03-8-20	05-9-22	1135	458	0.17		8.2	
Flood irrigation	LC07	Wheat–maize	03-8-20	04-9-28	702	300	0.58	0.50	23.5	20.6
	LC08	Wheat–maize	03-8-20	05-9-22	1135	675	0.42		17.7	
Non-irrigation	LC10	Non-cultivation	03-8-20	04-9-29	702	0	0.32	0.27	18.5	17.3
	LC81	Non-cultivation	03-11-9	05-9-22	934	0	0.22		16.1	
Stalk mulch	LC82	Wheat–maize	03-11-9	04-9-28	501	300	0.60	0.52	24.3	21.5
	LC83	Wheat–maize	03-11-9	05-9-23	934	675	0.44		18.7	
No stalk mulch	LC84	Wheat–maize	03-11-9	04-9-28	501	300	0.80	0.68	32.4	28.1
	LC85	Wheat–maize	03-11-9	05-9-23	934	675	0.56		23.8	

concentration of the tritium below 1.6 m in these profiles was about 859.2–2979.3 TU. The values were much larger than the average concentration of the tritium (21.70 TU) in rainfall in Hengshui and tritium concentration (14–80 TU) in groundwater in Hebei Plain (Liu et al., 1997; Zhou et al., 1998). This indicates the tracer moved downward obviously, which implied groundwater recharge occurred certainly. But the recharge cannot be calculated by the changes of tracer peaks. A possible explanation is that soil water movement may have been strongly affected by the water table. This movement was downward during precipitation and irrigation, and upward during evapotranspiration, so that the tracers moved both up and down with the soil water, keeping them relatively high in the soil profile, and increasing uncertainty. Applied tracer methods may be not directly applicable in such areas of shallow water table.

Comparison of tritium and bromide tracing (Fig. 15) shows that bromide indicates greater recharge rates. On average, bromide moved 23% faster (9 of 15 cases were fas-

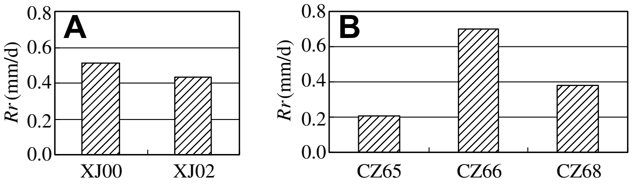

Figure 11 Recharge rates (*Rr*) of different land use. (A) Xinji: XJ00 peanut, JX02 peach. (B) Cangzhou: CZ65 Non-cultivation, CZ66 Vegetable, CZ68 Wheat–maize.

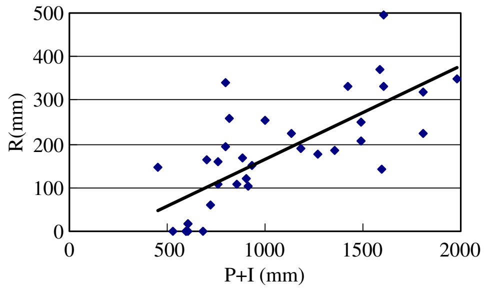

Figure 12 Recharge versus precipitation and irrigation for the experiment periods.

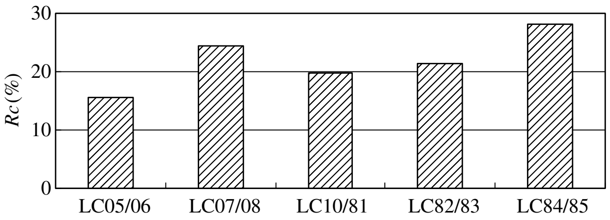

Figure 14 Averaged recharge coefficient (*Rc*) of different irrigation regime and cultivation practices determined by tritium tracing for wheat–maize fields in Luancheng. LC05/06 sprinkling irrigation; LC07/08 flood irrigation; LC10/81 non-irrigation non-cultivation; LC82/83 stalk mulch with flood irrigation; LC84/85 no stalk mulch with flood irrigation.

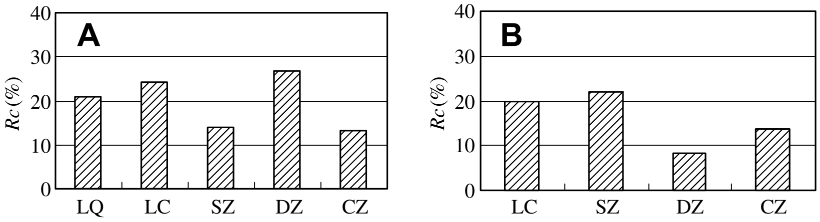

Figure 13 Recharge coefficient (*Rc*) of the different representative zones. (A) Flood-irrigated cropland; (B) non-irrigated non-cultivated land.

Table 6 Recharge rates and their variability during the experiment periods

Number	Land use	Calculating time	Δt (d)	$P + I$ (mm)	Rr (mm/d)		$(P + I)/\Delta t$ (mm/d)
					^{3}H	Br$^-$	
LC05	Wheat—maize, sprinkling irrigation	03-8-20—04-9-28	405	860	0.23	0.30	2.12
		04-9-28—05-9-22	359	733	0.10	0.09	2.04
LC06		03-8-20—05-9-22	764	1593	0.17	0.20	2.09
LC07	Wheat—maize, flood irrigation	03-8-20—04-9-28	405	1002	0.58	0.67	2.47
		04-9-28—05-9-22	359	808	0.24	0.14	2.25
LC08		03-8-20—05-9-22	764	1810	0.42	0.42	2.37
LC82	Wheat—maize, stalk mulch	03-11-9—04-9-28	324	801	0.60	0.60	2.47
		04-9-28—05-9-23	360	808	0.30	0.47	2.25
LC83		03-11-9—05-9-23	684	1609	0.44	0.53	2.35
LC84	Wheat—maize, no mulch	03-11-9—04-9-28	324	801	0.80	1.30	2.47
		04-9-28—05-9-23	360	808	0.34	0.52	2.25
LC85		03-11-9—05-9-23	684	1609	0.56	0.89	2.35
DZ17	Maize—cotton, flood irrigation	03-8-23—04-9-23	397	798	0.65	0.65	2.01
		04-9-23—05-9-27	369	760	0.07	0.34	2.06
DZ18		03-8-23—05-9-27	766	1558	0.37	0.50	2.03
CZ11	Non-cultivation, non-irrigation	03-8-22—04-9-21	396	758	0.27	—	1.91
		04-9-21—05-9-28	372	599	0.21	—	1.61
CZ12		03-8-22—05-9-28	768	1357	0.24	—	1.77
CZ13	Wheat—maize, flood irrigation	03-8-22—04-9-21	396	923	0.31	—	2.33
		04-9-21—05-9-28	372	771	0.27	—	2.07
CZ14		03-8-22—05-9-28	768	1694	0.29	—	2.21

Note: P = precipitation and I = irrigation.

ter and 6 were the same; the largest was 62%) than the tritiated water (Table 3). This result is almost in agreement with the lysimeter experiment result of Porro and Wierenga (1993), in which bromide moved approximately 20% faster than tritiated water. The faster bromide transport may be a result of anion exclusion (James and Rubin, 1986; Porro and Wierenga, 1993). Bromide ions in solution, being negative, are repelled by the generally negative particle surfaces, and therefore tend to concentrate in the water in the middle of a pore, which is normally more mobile. Bromide is relatively cheap and easy to detect. Being an integral part of the water molecule, tritium is close to an ideal tracer of water. Its concentration within the pore water is essentially uniform, regardless of mobility or proximity to solid surfaces, though it may be affected by exchange with water previously present in the soil. Tritium moves with the water and is not subject to anion exclusion. Drawbacks are that tritium requires relatively expensive measurement equipment and its use may be prohibited by environmental protection laws.

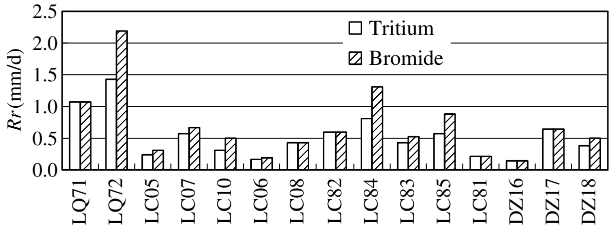

Figure 15 Comparison of the recharge rates (Rr) by tritium and bromide tracing.

Considering the similar climate character, the tracer results in India were compared with ours in Hebei Plain. Table 7 summarizes some recharge determined by tritium tracing by other authors in India. Fig. 16 compares the results from India and ours in the Hebei Plain, showing recharge is approximately proportional to water input. Additionally, at the same water input, the recharge in Hebei Plain almost is larger than that in India. That is to say, the recharge coefficients in Hebei Plain are bigger than that in India. The statistical results also showed that, the average recharge coefficient in Heibei Plain and India is 15.5% and 11.0%, respectively.

Regionalization of recharge or further work

The variations of groundwater recharge resulting from rainfall or irrigation reflect differences in various factors, including thickness and hydraulic properties of the unsaturated zone, rainfall patterns, irrigation types and regime, land use, evapotranspiration, etc. Regional groundwater recharge need to be estimated on the point measurements and zoning of above factors. Sophocleous (1992) presented the combination of multiple regression and GIS overlay analysis as a powerful and practical approach to regionalizing small samples of recharge estimates, which may be applied in the research area. However the required data for region-

Table 7 Recharge calculated by injected tritium in India

References	Location	Number of sites	Recharge (mm)	Water input (mm)	*Rc* (%)	Memo
Goel et al. (1975)	Western Uttar Pradesh	45	215.0	990	21.7	Alluvial deposits
	Punjab	21	82.0	460	17.8	
	Haryana	14	80.0	470	17.0	
Athavale et al. (1983)	Godavari-Puma	24	56.6	652	8.7	Basalt
	Kukadi basin	19	46.0	612	7.5	
Sukhija et al. (1996)	Jodhpur	1	25.7	219	11.7	Aeolian deposits
		1	22.1	219	10.1	
		1	46.8	389	12.0	
		1	16.6	219	7.6	
		1	17.4	219	8.0	
		1	21.8	389	5.6	
Sukhija et al. (1996)	Jam river basin	28	131.3	1067	12.3	1988
		22	83.5	761	11.0	1989
		21	95.1	978	9.7	1990
		20	56.9	657	8.7	1991
Chand et al. (2004)	The Bairasagara watershed, Kolar district, Karnataka	36	66.1	968	6.8	Reddish sandy soil
Average					11.0	

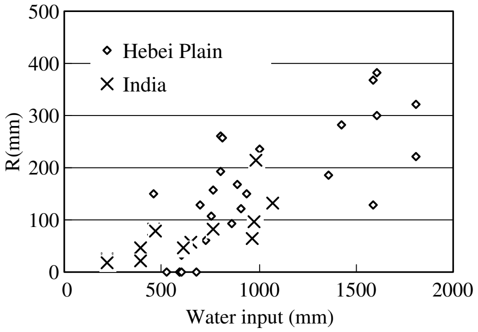

Figure 16 Recharge determined by tritium tracing in Hebei Plain compared with that in India.

alizing are not available. Therefore, further study needs collecting regional distribution data mentioned above and determining recharge rates for more sites and longer time on each homogeneous zone because the specific recharge sites are limited to a few homogeneous zones over two years in the study area. After get site-specific recharges of each homogeneous zone (considering thickness and hydraulic properties of the unsaturated zone, rainfall patterns, irrigation types and regime and land use) for different hydrological year, multiple variables statistical analysis will be applied to obtain the regression equation for the main factors. Then recharge can be estimated separately for each homogeneous zone. Each factor used to zones of the study area for recharge calculations should be mapped on a separate overlay; finally the overlays (maybe including land use, rainfall and irrigation patterns, isolines of water table depth, irrigation rate and rainfall, and hydraulic conductivities of the unsaturated zone) should be combined to produce a master map of homogeneous zones.

Conclusions

Average recharge rates and recharge coefficients determined by tritium and bromide tracing for different sites in the Hebei plain from 2003 to 2005 were 0.00–1.05 mm/d and 0.0–42.5%, respectively. The variation in recharge rates and recharge coefficient reflects the different crops, cultivation practices, irrigation regimes, and soil types. (1) Flood irrigation resulted in more recharge compared to non-irrigation and sprinkling irrigation land. Water-saving irrigation reduced recharge rates even below those of non-irrigated non-cultivated land. (2) Different land use resulted in different recharge rates. Under certain conditions, the recharge rate for vineyards was greater than that for apple orchards. The recharge rate for peanut was greater than that for peach and the recharge rate for vegetables (e.g. Chinese cabbage and garlic) was greater than that for wheat–maize mainly due to vastly different amount of irrigation applied for vegetables. (3) Straw mulch resulted in reduced recharge.

Recharge rates estimated from the first year of tracer travel were greater than those estimated from the second year. This difference results at least in part from temporal variability of total precipitation and irrigation.

Advantages of the applied tracer method include investigator control over the timing, placement, and amount of tracer. It is possible to avoid the complexities of the top meter of soil (action of roots, numerous preferential flow channels, and cultural disturbances) if tracers are injected below 1 m depth. Disadvantages include that the method may not be applicable for areas of shallow water table (less than 3 m), when more frequent monitoring may be needed to trace water movement, and that it is time-consuming, especially in areas of rainfall and irrigation shortage.

This study also affords direct comparison, in a field study of recharge rates, of the near-ideal tritium tracer with the more common but less ideal bromide. On average the bromide moved 23% faster than the tritiated water, possibly as a result of anion exclusion.

Acknowledgements

The authors gratefully acknowledge the financial support by the China Geology Survey (200310400035-1), the National Natural Science Foundation of China (40472123, 40602031) and the Research Foundation for Outstanding Young Teachers, China University of Geosciences, Wuhan (CUGQNL0631).

References

Allison, G.B., Hughes, M.W., 1978. The use of environmental chloride and tritium to estimate total recharge to an unconfined aquifer. Australian Journal of Soil Research 16, 181–195.

Allison, G.B., Hughes, M.W., 1983. The use of natural tracers as indicators of soil–water movement in a temperate semi-arid region. Hydrogeology Journal 60, 157–173.

Allison, G.B., Gee, G.W., Tyler, S.W., 1994. Vadose zone techniques for estimating groundwater recharge in arid and semiarid regions. Soil Science Society of America Journal 58, 6–14.

Athavale, R.N., Rangarajan, R., 1988. Natural recharge measurements in the hard-rock regions of semi-arid India using tritium injection – a review. In: Simmers, I. (Ed.), Estimation of Natural Groundwater Recharge. D. Reidel Publishing Company, Dordrecht, The Netherlands, pp. 175–195.

Athavale, R.N., Murti, C.S., Chand, R., 1980. Estimation of recharge to the phreatic aquifers of the Lower Maner Basin, India, by using the tritium injection method. Journal of Hydrology 45, 185–202.

Athavale, R.N., Chand, R., Rangarajan, R., 1983. Groundwater recharge estimates for two basins in the Deccan Trap Basalt formation. Hydrological Sciences Journal 28 (4), 525–538.

Chand, R., Chandra, S., Rao, V.A., Singh, V.S., Jain, S.C., 2004. Estimation of natural recharge and its dependency on sub-surface geoelectric parameters. Journal of Hydrology 299, 67–83.

Cook, P.G., Jolly, I.D., Leaney, F.W., Walker, G.R., 1994. Unsaturated zone tritium and chlorine 36 profiles from southern Australia: their use as tracers of soil water movement. Water Resources Research 30, 1709–1719.

De Vries, Jacobus J., Simmers, I., 2002. Groundwater recharge: an overview of processes and challenges. Hydrogeology Journal 10, 8–15.

Dincer, T., Al-Mugrin, A., Zimmermann, U., 1974. Study of the infiltration and recharge through the sand dunes in arid zones with special reference to stable isotopes and thermonuclear tritium. Journal of Hydrology 23, 79–109.

Edson, T.D., 1998. Tracer Studies and Groundwater Recharge Assessment in the Eastern Fringe of the Botswana Kalahari. Printing & Publishing Company Botswana (Pty) Limited, Gaborone, Botswana, pp. 19–26.

Flury, M., Fluhler, H., Jury, W.A., Leuenberger, J., 1994. Susceptibility of soils to preferential flow of water: a field study. Water Resources Research 30, 1945–1954.

Forrer, I., Kasteel, R., Flury, M., Fluhler, H., 1999. Longitudinal and lateral dispersion in an unsaturated field soil. Water Resources Research 35, 3049–3060.

Goel, P.S., Datta, P.S., Rama, Sangal, S.P., Hans Kumar, Prakash Bahadur, Sabherwal, P.K., Tanwar, B.S., 1975. Tritium tracer studies on groundwater recharge in the alluvial deposits of Indo-Gangetic Plains of Western U.P., Punjab and Haryana. In: Athavale, R.N., Srivastava, V.B. (Eds.), Approaches and Methodologies for Development of Groundwater Resources: Indo-German Workshop, Hyderabad, India, Proceedings, National Geophysical Research Institute, pp. 309–322.

Hendrickx, J.M.H., Dekker, L.W., Boersma, O.H., 1993. Unstable wetting fronts in water-repellent field soils. Journal of Environmental Quality 22, 109–118.

James, R.V., Rubin, J., 1986. Transport of chloride ion in a water-unsaturated soil exhibiting anion exclusion. Soil Science Society of America Journal 50 (5), 1142–1149.

Jin, Menggui, Simmers, Ian, Zhang, Renquan, 1998. Preliminary estimation of groundwater recharge at Wangtong, Hebei, P.R. China. In: Brahana, J.V. et al. (Eds.), Gambling with Groundwater: Physical, Chemical and Biological Aspects of Aquifer-stream Relations, Las Vegas, NV, USA, pp. 407–412.

Jin, M.G., Zhang, R.Q., Sun, L.F., Gao, Y.F., 1999. Temporal and spatial soil water management: a case study in the Heilonggang region, PR China. Agricultural Water Management 42, 174–187.

Jin, Menggui, Liang, Xing, Simmers, Ian, Gao, Yunfu, Zhang, Renquan, 2000a. Estimation of groundwater recharge using artificial tritium tracing. In: Proceedings of the International Symposium on Hydrogeology and the Environment, Wuhan, China, 17–21 October 2000. China Environmental Science Press, pp. 340–345.

Jin, Menggui, Simmers, Ian, Zhang, Renquan, 2000b. Estimation of Groundwater Recharge at Wangtong, Hebei (Report), China University of Geosciences, Wuhan, China and Free University, Amsterdam, The Netherlands.

Jury, W.A., Stolzy, L.H., Shous, P., 1982. A field test of the transfer function model for predicting solute movement. Water Resources Research 18, 369–375.

Kung, K.J., 1990. Influence of plant uptake on the performance of bromide tracer. Soil Science Society of America Journal 54, 975–979.

Lin, R.F., Wei, K.Q., 2006. Tritium profiles of pore water in the Chinese loess unsaturated zone: implications for estimation of groundwater recharge. Journal of Hydrology 328, 192–199.

Liu, C.F., Wang, P.Y., Zhou, L., 1997. The environment significance of H, O, C and Cl isotopic composition in groundwater of Hebei plain (in Chinese). Earth Science Frontiers 4 (1–2), 267–274.

Nativ, R., Adar, E., Dahan, O., Geyh, M., 1995. Water recharge and solute transport through the vadose zone of fractured chalk under desert conditions. Water Resources Research 31, 253–261.

Nimmo, J.R., Healy, R.W., Stonestrom, D.A., 2005. Aquifer recharge. In: Anderson, M.G., Bear, J. (Eds.), Encyclopedia of Hydrological Science, vol. 4. Wiley, Chichester, UK, pp. 2229–2246, <http://www.mrw.interscience.wiley.com/ehs/articles/hsa161a/frame.htm>.

Phillips, F.M., 1994. Environmental tracers for water movement in desert soils of the American Southwest. Soil Science Society of America Journal 58, 14–24.

Porro, I., Wierenga, P.W., 1993. Transient and steady-state solute transport through a large unsaturated soil column. Ground Water 31 (2), 193–200.

Rangarajan, R., Athavale, R.N., 2000. Annual replenishable groundwater potential of India: an estimate based on injected tritium studies. Journal of Hydrology 234, 38–53.

Rangarajan, R., Muralidharan, D., Deshmukh, S.D., Hodlur, G.K., Gangadhara Rao, T., 2005. Redemarcation of recharge area of stressed confined aquifers of Neyveli groundwater basin, India, through tritium tracer studies. Environmental Geology 48, 37–48.

Rice, R.C., Bowman, R.S., Jaynes, D.B., 1986. Percolation of water below an irrigated field. Soil Science Society of America Journal 50, 855–859.

Saxena, R.K., Dressie, Z., 1984. Estimation of Groundwater Recharge and Moisture Movement in Sandy Formations by Tracing Natural Oxygen-18 and Injected Tritium Profiles in the Unsaturated ZoneIsotope Hydrology 1983. International Atomic Energy Agency, Vienna, pp. 139—150.

Scanlon, B.R., 1992. Evaluation of liquid and vapor flow in desert soils based on chlorine-36 and tritium tracers and nonisothermal flow simulations. Water Resources Research 28, 285—297.

Scanlon, B.R., 2000. Uncertainties in estimating water fluxes and residence times using environmental tracers in an arid unsaturated zone. Water Resources Research 36, 395—409.

Scanlon, B.R., Healy, R.W., Cook, P.G., 2002. Choosing appropriate techniques for quantifying groundwater recharge. Hydrogeology Journal 10 (1), 18—39.

Sekhar, M., Rasmi, S.N., Sivapullaia, P.V., Ruiz, L., 2004. Groundwater flow modeling of Gundal sub-basin in Kabini river basin, India. Asian Journal of Water Environmental Pollution 1 (1—2), 65—77.

Sharma, M.L., Watson, J.D., Cresswell, I.D., 1987. Estimation of areal recharge using a non-reactive chemical tracer. In: Fok, Y.-S. (Ed.), Infiltration-principles and Practices. University of Hawaii, Honolulu, Hawaii, pp. 316—325.

Shen, Y., Huang, X., Wang, H., 1998. Field effects of straw mulching (in Chinese). Agricultural Research in the Arid Area 16 (1), 45—50.

Simmers, I. (Ed.), 1997. Recharge of Phreatic Aquifers in (Semi)-arid Areas. IAH International Contributions to Hydrogeology, vol. 19. A.A. Balkema, Rotterdam, pp. 19—98.

Sophocleous, M.A., 1992. Groundwaters recharge estimation and regionalization: The Great Bend Prairie of Central Kansas and its recharge statistics. Journal of Hydrology 137, 113—140.

Sukhija, B.S., Reddy, D.V., Nagabhushanam, P., Hussain, Syed, Giri, V.Y., Patil, D.J., 1996. Environmental and injected tracers methodology to estimate direct precipitation recharge to a confined aquifer. Journal of Hydrology 177, 77—97.

Tyler, S.W., Walker, G.R., 1994. Root zone effects on tracer migration in arid zones. Soil Science Society of America Journal 58 (1), 25—31.

Wang, Qunying, Luo, Zejiao, Wang, Ping, 2004. Experimental research of testing Br^- in soil using ion selective electrode method (in Chinese). Geological Science and Technology Information 23 (3), 93—96.

Wood, W.W., Sanford, W.E., 1995. Chemical and isotopic methods for quantifying ground-water recharge in a regional, semiarid environment. Ground Water 33, 458—468.

Zhou, L., Liu, C.F., Wang, P.Y., 1998. Isotopic composition of saline water in quaternary aquifers of Hebei plain (in Chinese). Hydrogeology and Engineering Geology (3), 4—8.

Zimmermann, U., Munnich, K.O., Roether, W., Schubach, K., Siegel, O., 1966. Tracers determine movement of soil moisture and evapotranspiration. Science 152, 346—347.

Zimmermann, U., Munnich, K.O., Roether, W., 1967. Downward Movement of Soil Moisture Traced by Means of Hydrogen Isotopes. Geophysical Monograph, vol. 11. American Geophysical Union, pp. 28—36.