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ORIGINAL ARTICLE

Using tracer tests to estimate vertical recharge and evaluate influencing factors for irrigated agricultural systems

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Abstract Accurate estimation of groundwater recharge is critical for (semi) arid regions, especially in places like the North China Plain (NCP) where recharge from irrigation and intermittent precipitation events comprises the largest portion of recharge. Tracer tests were used to estimate potential recharge beneath agricultural systems irrigated by groundwater, and to help delineate factors that influence recharge. A bromide solution was applied below root regions to trace infiltration in the vadose zone beneath irrigated agricultural fields and non-irrigated woodlands at both piedmont plain (Shijiazhuang) and alluvial and lacustrine plain areas (Hengshui) in the NCP. The tracer tests lasted for more than 2 years and were conducted at 37 subsites grouped in sets of two to four at 12 regionally distributed sites. For the piedmont plain sites, the potential recharge rate ranged between 37–466 mm/a (6–27% of precipitation plus irrigation, $P + I$) beneath wheat-maize, 110–564 mm/a (12–52% of $P + I$) beneath orchard, and 7–10 mm/a (1–2% of $P + I$) beneath woodlands. For the alluvial and lacustrine plain sites, the potential recharge rate ranged between 14–177 mm/a (2–20% of $P + I$) beneath wheat-maize, 6–57 mm/a (0.5–5% of $P + I$) beneath orchard, 87–279 mm/a (10–31% of $P + I$) beneath cotton, and 6–44 mm/a (1–8% of $P + I$) beneath woodlands. The potential recharge was impacted by various external factors, like lithology, crops, and irrigation. When an irrigation controlled experiment was conducted in the same field with the same crop cultivation, the results revealed that larger irrigation quantities led to larger potential recharge rates.

Keywords Tracer tests · Bromide · Groundwater recharge · Irrigation · Vadose zone · China

Introduction

Groundwater is essential worldwide for meeting the fresh water demand for urban, agriculture, and industry uses, particularly in (semi) arid regions such as the North China Plain (NCP, Fig. 1) that lack surface water. Agriculture is significant in the NCP, consuming approximately 70% of the total water (Lu et al. 2011). Total recharge in the NCP, numerically calculated by modified Modflow 2005, averaged 23.75 billion m^3/a from 2000 to 2010, while the discharge averaged 26.11 billion m^3/a (see Table 1). For decades, groundwater overdraft (2.3 billion m^3/a in excess of recharge), especially for agriculture use in this densely populated semiarid plain, has led to continuous decline of the water table (Fei et al. 2009). This overdraft negatively affects the hydrological balance and makes groundwater management much more complex. Groundwater recharge in the NCP is mainly from infiltration associated with local precipitation events and excess irrigation flow (i.e., vertical recharge through the vadose zone) (e.g., Gong et al. 1993; Wang 2008; Chen et al. 2011; Cao et al. 2006). The amount of recharge or potential recharge that occurs through

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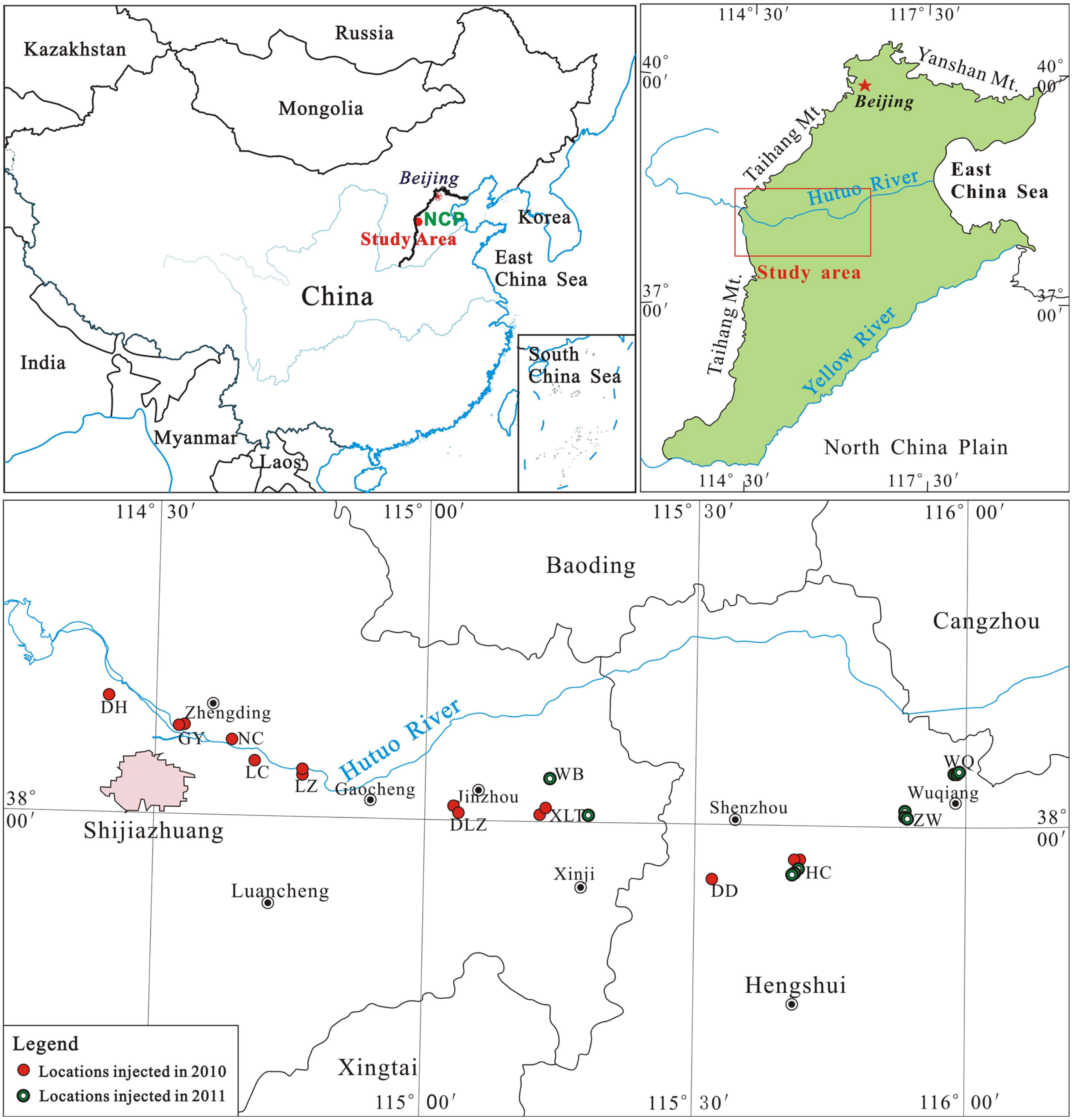

Fig. 1 Tracer test locations

infiltration remains a critical issue for groundwater management in the NCP. Recharge is herein defined as the percolation arriving at the water table (Rushton 1997). Potential recharge is herein defined as the water that reaches the bottom of the root zone or the maximum evaporation depth (Rushton 1997) and thus is no longer affected by evapotranspiration. This potential recharge can be a reflection of the recharge quantity, although the water has not reached the saturated zone yet (there may be a delay between actual recharge and potential recharge particularly when the water table is deep). In addition, the estimation of recharge at water table overestimates recharge quantity when the water table is continuously declining (Huo et al. 2014).

A variety of methods have been used to estimate recharge or potential recharge from infiltration in (semi) arid plains, including tracer tests, physical methods, and simulation methods (e.g., Allison et al. 1994; de Vries and

Table 1 Average value of groundwater balance in the North China Plain in the years 2000–2010

Recharge				
Precipitation infiltration	Other vertical infiltration	Lateral inflow	Leakage inflow	Total
17.94	4.32	1.44	0.05	23.75
Discharge				
Abstraction	Phreatic water evaporation	Lateral outflow	Leakage outflow	Total
18.09	5.77	0.54	1.71	26.11
Recharge minus discharge				−2.36

Unit: $\times 10^9$ m^3/a

All the values were numerically calculated by modified Modflow 2005

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Simmers 2002; Wang 2008). Environmental (i.e., resident) tracers, including Cl^-, SO_4^{2-}, and stable isotopes (e.g., ^2H, ^{18}O), have been considered to be applicable and effective to estimate recharge in (semi) arid regions (e.g., Walker et al. 1991; Bromley et al. 1997; Scanlon et al. 2006, 2010; Zagana et al. 2007; Houston 2007; Li et al. 2007; Gates et al. 2008; Lin et al. 2013). However, environmental tracers in some cases may have limited use for irrigated agriculture since there might be multiple sources. Applied tracers (e.g., dyes, tritiated water, and bromide) are a standard option to avoid these problems. Dyes have primarily been used to investigate preferential flow (e.g., Delin and Landon 2002; Flury et al. 1994; Forrer et al. 1999; Kung 1990; Scanlon and Goldsmith 1997). The use of tritiated water is forbidden in most regions because of environmental protection laws (Scanlon et al. 2002). Bromide, which is considered conservative, has not been so widely used for recharge estimation because of its low content in natural soil and groundwater (Sharma et al. 1987; Rice et al. 1986; Wang et al. 2008a; Tan 2012).

The main objectives of this research are to investigate the relative contributions of precipitation and irrigation to local recharge for the NCP, and to estimate the potential recharge rates (all of the recharge calculated in this article stands for potential recharge) to support future basin-scale modeling. An additional aim is to examine the impact of different agricultural land uses on potential recharge. Several 2-year-long bromide tracer tests were conducted in the piedmont and alluvial/lacustrine plain areas in the NCP.

Background

The NCP can be separated into three sections from west to east, the piedmont plain, alluvial and lacustrine plains, and the coastal plain. The field experiments were conducted at Shijiazhuang (piedmont plain) and Hengshui (alluvial and lacustrine plains), both regions of which have thick (~10–55 m) vadose zones. The study area is located at longitude 114°24′–115°59′E and latitude 37°52′–38°9′N (Fig. 1), with surface topography sloping from west to east.

Because of the temperate continental monsoon climate, precipitation is highly variable both spatially and temporally for both locations. Mean annual precipitation is between 400 and 600 mm, 80% of which falls between July and September (Lu et al. 2011). At Shijiazhuang Weather Station, the average annual precipitation was 526 mm, the maximum was 1097 mm, and the minimum was 226 mm from 1960 to 2012. The annual precipitation during the experiment period was 341 mm in 2010, 501 mm in 2011, and 413 mm in 2012. At Hengshui Weather Station, the average annual precipitation was 469 mm, the maximum was 826 mm, and the minimum was 234 mm from 1991 to 2012. The annual precipitation during the experiment period was 440 mm in the year 2010, 452 mm in 2011, and 618 mm in 2012. Average annual temperature was 13.5 °C (1960–2010), and average annual surface water evaporation was 1677.8 mm, according to statistical data collected from 1972 to 2008 for 17 observing stations in Shijiazhuang city (Han et al. 2009). While groundwater levels fluctuate seasonally, they have been declining over the entire region for decades (even more than 50 m) because of over-exploitation (Fei et al. 2009).

The study areas have large cultivated land areas, with rotated winter wheat and summer maize (hereafter called wheat-maize for short) and cotton as the primary crops. Winter wheat is mainly sown at the beginning of October and harvested in mid-June, while the summer maize is sown in mid-June and harvested at the beginning of October. Cotton is commonly sown in the mid-April and harvested at the end of September. The crops need additional water, beyond what is supplied by precipitation, to meet their growth requirements. The water requirement is greatest for winter wheat, followed by cotton and then summer maize. Generally, landowners irrigate winter wheat 3–4 times per season, cotton 2–3 times, and summer maize 1–2 times. Through investigation data from Wang et al.

(2008b) we know that for winter wheat: The landowner's preference of irrigation period is the regeneration stage (at the beginning of March), wintering stage (at the end of November), filling stage (at the end of May), then, preplanting stage (at the beginning of October). For summer maize, the landowner's preference of irrigation period is the additional fertilizer stage (at the middle of July), then, seedling emergence stage (at the middle of June) (Wang et al. 2008b). For cotton, irrigation would be applied at sowing stage (at the middle of May), squaring stage (at the middle of June), full-bloom stage and flowering (at the middle of July), and boll-forming stage (at the end of July). Irrigation application depends whether it is a rainy, normal, or dry year. Normally, summer maize would be irrigated once and cotton would be irrigated thrice per growing season. Irrigation application would be reduced once during rainy years and increased once during dry years.

Recharge to the NCP aquifers under natural conditions primarily occurs via infiltration of precipitation. Mountain-front recharge occurs along the front of Taihang Mountain and Yanshan Mountain to the west and north of the NCP (Fig. 1) and comprises a secondary source of recharge. For agricultural areas, irrigation return flow provides another source of recharge. Pumping and evapotranspiration are the main discharges from the aquifer systems.

The lithology is mainly loam and silt in the study area. The soil is generally finer at the alluvial and lacustrine plains than that at the piedmont plain. Specific properties of the topsoil are presented in Table 2.

Materials and methods

Bromide, in the form of saturated sodium bromide solution (~412 g/L), was applied to trace infiltration in the vadose zone beneath the irrigated agricultural fields and non-irrigated woodlands at both the piedmont and alluvial/lacustrine plain in the NCP. The tracer tests and monitoring lasted for more than 2 years and were conducted at 37 subsites grouped in sets of two to four at 12 regionally distributed sites. For each of the 12 sites, the subsites were separated by approximately 1–2 km and comprised different land uses. The subsites were regarded as comparison experiments to investigate the impact of different crop covers (winter wheat, summer maize, cotton, etc.) and irrigation (or non-irrigation) schedules. For these experiments, the only irrigation the fields received was that applied by the landowners. In addition to these tests, a controlled irrigation experiment was conducted at a single wheat and maize site with six locations (HC05 to HC10, see Tables 2, 3). Information concerning crop type, injection and sampling dates, and irrigation schedules is presented in Table 3. Five of the test locations (DH02, GY03, NC02, DD01, and DD02, see Tables 2, 3) were eventually abandoned because of various external disturbances. To obtain a background concentration of bromide, soil samples were collected in profiles with an interval of 20 cm to a depth of 5 m at each subsite together with tracer application. Background samples revealed low bromide concentrations. Most of concentrations were lower than the detection limit, indicating bromide was an appropriate artificial tracer in this area.

The study by Feng and Liu (1998) demonstrated that water uptake by winter wheat roots occurred primarily above the depth of 1.2 m. In addition, Zhang (1999) pointed out that the maximum rooting depth of summer maize was 1.2 m in Piedmont Plain of Taihang Mountain, the western part of NCP. Evapotranspiration was considered negligible below this depth. Thus, the tracer tests involved injection of 20 mL of tracer solution into a 2-cm-diameter vertical borehole at a depth of 1.2 m, which may have avoided or significantly reduced the influence of the soil complexities within the 1.2 m top soil (action of roots,

Table 2 Basic information for each site in the study area

Study area	Sites (abbreviations or labels)	Lithology (USDA)	Water table depth (m)	Average precipitation (mm/a)
Piedmont plain	Dahe, Luquan (DH)	Sandy loam	26.5	525.7 (1960–2010)
	Gaoying, Chang'an (GY)	Sandy loam	>50	525.7 (1960–2010)
	Nancun, Chang'an (NC)	Sandy loam		525.7 (1960–2010)
	Liangcun, Gaocheng (LC)	Loam		525.7 (1960–2010)
	Lianzhou, Gaocheng (LZ)	Loam	37.5	525.7 (1960–2010)
	Donglizhuang, Jinzhou (DLZ)	Silt		482.9 (2003–2012)
Alluvial and lacustrine plains	Xinleitou, Xinji (XLT)	Silt	45.6	462.1 (2003–2012)
	Weibo, Xinji (WB)	Silt	42.1	462.1 (2003–2012)
	Dadi, Shenzhou (DD)	Silt loam	3.1	455.9 (2000–2007)
	Huchi, Shenzhou (HC)	Silt loam	8.3–11.2	455.9 (2000–2007)
	Zhouwo, Wuqiang (ZW)	Clay	9.8	463.5 (2003–2012)
	Wuqiang, Wuqiang (WQ)	Clay	6.7	463.5 (2003–2012)

Table 3 Detailed description of tracer tests at each location

Study area	Location	Crop type	Irrigation times per year	Injection date	1st sampling date	2nd sampling date	3rd sampling date
Piedmont plain	DH01	Poplar	0	8/26/2010	10/22/2011	–	–
	DH02	W-M	2–3 for maize, 3–4 for wheat	8/26/2010	10/22/2011	7/7/2012	10/23/2012
	DH03	Apple		8/26/2010	10/22/2011	7/7/2012	10/23/2012
	DH04	W-M	2–3 for maize, 3–4 for wheat	7/7/2012	10/23/2012	–	–
	GY01	Abandoned peach	0	8/24/2010	10/22/2011	–	–
	GY02	W-M	1–2 for maize, 4 for wheat	8/24/2010	10/22/2011	7/8/2012	–
	GY03	Uncultivated	0	8/24/2010	–	–	–
	NC01	W-M	1–2 for maize, 4 for wheat	8/25/2010	10/23/2011	7/6/2012	10/25/2012
	NC02	Poplar	0	8/25/2010	–	–	–
	LC01	Apple	Once in dry years, 0 for others	8/27/2010	10/24/2011	7/10/2012	10/24/2012
	LC02	W-M	1–2 for maize, 4 for wheat	8/27/2010	10/24/2011	7/8/2012	10/24/2012
	LC03	W-M	1–2 for maize, 4 for wheat	7/8/2012	10/24/2012	–	–
	LZ01	W-M	1–2 for maize, 4 for wheat	8/25/2010	10/24/2011	7/7/2012	10/25/2012
	LZ02	Poplar	0	8/25/2010	10/24/2011	7/6/2012	–
	DLZ01	Pear	6–7	9/4/2010	10/16/2011	7/17/2012	10/15/2012
	DLZ02	Grape	10	9/4/2010	10/16/2011	7/17/2012	10/15/2012
	DLZ03	One season maize, then change to poplar	1–2 for maize	9/4/2010	10/16/2011	7/17/2012	10/15/2012
Alluvial and lacustrine plains	XLT01	Peach		9/3/2010	10/20/2011	7/14/2012	10/16/2012
	XLT02	W-M	1–2 for maize, 4 for wheat	9/3/2010	10/20/2011	7/14/2012	10/16/2012
	XLT03	Locust		9/3/2010	10/20/2011	7/14/2012	10/16/2012
	XLT04	Cotton		6/26/2011	10/21/2011	7/15/2012	10/20/2012
	WB01	Pear		7/4/2011	10/20/2011	7/15/2012	10/20/2012
	WB02	Poplar		7/4/2011	10/20/2011	7/15/2012	10/20/2012
	WB03	W-M		7/12/2011	10/20/2011	7/14/2012	10/20/2012
	DD01	Poplar	0	9/5/2010	10/14/2011	7/18/2012	
	DD02	Cotton	Seldom	9/5/2010	–	–	–
	DD03	W-M	1–2 for maize, 4 for wheat	9/5/2010	10/14/2011	7/18/2012	10/14/2012
	HC02	Poplar	0	6/27/2011	10/12/2011	–	–
	HC03	Cotton		6/28/2011	10/12/2011	7/22/2012	10/22/2012

Table 3 continued

Study area	Location	Crop type	Irrigation times per year	Injection date	1st sampling date	2nd sampling date	3rd sampling date
	HC04	W-M	1–2 for maize, 4 for wheat	6/28/2011	10/17/2011	7/11/2012	10/21/2012
	HC05	W-M	1 for maize, 3–4 for wheat	7/22/2011	10/13/2011	7/16/2012	10/13/2012
	HC06	W-M	1 for maize, 3 for wheat	7/22/2011	10/13/2011	7/16/2012	10/13/2012
	HC07	W-M	1 for maize, 0 for wheat	7/22/2011	10/13/2011	7/16/2012	–
	HC08	W-M	1 for maize, 2 for wheat	7/22/2011	10/13/2011	7/16/2012	10/14/2012
	HC09	W-M	1 for maize, 1 for wheat	7/22/2011	10/13/2011	7/16/2012	10/14/2012
	HC10	W-M	1 for maize, 4 for wheat	7/22/2011	10/13/2011	7/16/2012	10/14/2012
	HC11	W-M	1–2 for maize, 4 for wheat	7/15/2012	10/21/2012	–	–
	ZW01	W-M	1–2 for maize, 4 for wheat	7/5/2011	10/15/2011	7/12/2012	10/12/2012
	ZW02	Poplar		7/5/2011	10/17/2011	7/13/2012	10/13/2012
	ZW03	Soybean		7/5/2011	10/17/2011	7/13/2012	10/13/2012
	WQ01	W-M	1–2 for maize, 4 for wheat	7/6/2011	10/15/2011	7/12/2012	10/12/2012
	WQ02	Poplar	0	7/6/2011	10/15/2011	7/12/2012	10/12/2012
	WQ03	Cotton	Seldom	7/6/2011	10/15/2011	7/12/2012	10/12/2012

Take “DH03” as an example, “DH” is a site (detailed site information see Table 2), “03” is the subsite (specific land use) for DH; W-M is short for the rotated winter wheat and summer maize

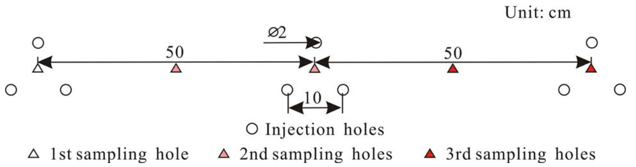

Fig. 2 Tracer injection and sampling holes layout (map view). *Note Triangles in the tri-circle* are main sampling holes, while the other two are secondary holes

numerous preferential channels, and culture disturbances). The injections were conducted before the rainy season. To minimize disruption, the boreholes were refilled with soil after tracer injection. The injection and sampling points were specially designed (see Fig. 2) in order to create an approximate planar (rather than pointlike) source of tracer over the specific area. The locations were recorded by a Garmin GPS (Global Positioning System). In addition, a 5-cm-long PVC (Polyvinylchloride) tube was buried at a depth of 40 cm at the center of the tri-circle as a marker for further sampling.

After tracer injection, soil samples were collected periodically to observe bromide transport and estimate recharge rates at the point-scale. Soil samples were collected by hand auger with intervals of 10–20 cm to a depth of 5 m below land surface. Each sample contained about 200 g and was stored in a plastic zip-lock bag. The soil volumetric moisture content was tested by a portable TDR (time domain reflectometer) in situ. For soil gravimetric moisture content, samples were collected using aluminum moisture boxes and capped as quickly as possible, weighed in the field immediately, then taken back to the laboratory and oven-dried to constant weight at a temperature of 105 °C.

Samples were air-dried and sieved with a 1-mm sieve. One hundred milliliters of deionized water was added to 20 g of air-dried sediment in an Erlenmeyer flask. The mixture was placed in a reciprocal shaker for more than 3 min and then centrifuged at 4000 r/min for 10 min to separate liquid from sediments. The supernatant fluid was analyzed by an ion selective electrode (PBr-1, 217, Shanghai Precision & Scientific Instrument Co., Ltd). The performance of the bromide selective electrode appears to have been constrained for some reason for the third sampling event (October 2012), leading to overall higher values. Fortunately, the data trends (e.g., concentration peaks) appear reasonable and consistent, thus these data are included in the discussion.

The recharge rate was estimated through observing the downward movement of tracer concentration peaks (Δz, L, 1.2 m was considered to be the initial peak depth on the injection date) through the vadose zone during a period of time (Δt, T). The recharge rate (R, L/T) was calculated by

$$R = v \cdot \theta = \frac{\Delta z}{\Delta t} \cdot \theta \tag{1}$$

where v is the downward velocity of the peaks, L/T; θ is averaged soil volumetric moisture content within the sampling depth, L^3/L^3. The recharge coefficient (R_c, dimensionless value) is the ratio of recharge rate and total water input (precipitation and irrigation return flow) and that is

$$R_c = \frac{R}{P + I} \tag{2}$$

where P is precipitation, L/T; and I is irrigation amount, L/T.

So as to know whether tracer in the secondary holes in Fig. 2 move downward synchronously with the main holes, two holes were sampled at the 2nd and 3rd sampling times. The results revealed that the concentration curve peaks are nearly at the same level which indicates that the tracer moved downward almost at a uniform rate, though bromide concentration in the secondary holes is less than that in the main holes.

Results and discussion

Tracer transport

Hereafter, the tracer transport refers to the downward movement of the bromide concentration peak. Table 4 presents the subsites for which minimal tracer transport was observed during the entire test or for a certain period of the test. These subsites are the ones that received little or no irrigation. At many of these subsites, the observed tracer movement is likely due only to the tracer injection. For example, minimal transport was observed for the woodlands and orchards sites regardless of lithology or seasons. In fact, "negative" transport was observed at subsite XLT03-2, possibly indicating the impact of evapotranspiration on upward soil moisture movement, which implies that the 1.2 m depth of tracer injection is not deep enough. In addition, minimal tracer transport was observed for irrigated subsites with small irrigation rates. For example, subsites XLT04-2, ZW03-2, WQ03-2 received small

Table 4 Location where minimal tracer transport was observed

Location/label	Duration time	P (mm)	I (mm)	Δt (days)	Δz (cm)
LZ02-1	8/25/2010 to 10/24/2011	787.3	0	426	5
WB02-1	7/4/2011 to 10/20/2011	260	0	109	5
WQ02-1	7/6/2011 to 10/15/2011	268.6	0	102	5
HC02	6/27/2011 to 10/12/2011	325	0	107	5
ZW02	7/5/2011 to 10/13/2012	795	0	466	5
DH01	8/26/2010 to 10/22/2011	784.8	0	422	5
GY01	8/24/2010 to 10/22/2011	784.8	0	424	5
DH03-3	7/8/2012 to 10/23/2012	373.6	0	108	0
LC01-2	10/25/2011 to 7/10/2012	328.9	0	260	0
LC01-3	7/11/2012 to 10/24/2012	327.4	0	106	0
LZ02-2	10/25/2011 to 7/6/2012	280.1	0	256	0
DLZ03-2	10/17/2011 to 7/17/2012	329.6	0	285	0
DLZ03-3	7/18/2012 to 10/15/2012	322.1	0	90	0
XLT03-2	10/21/2011 to 7/14/2012	131	0	268	<0
WB02-2	10/21/2011 to 7/15/2012	156.7	0	269	0
WQ02-2	10/16/2011 to 7/12/2012	170	0	271	0
XLT04-2	10/22/2011 to 7/15/2012	156.7	130	268	0
ZW03-2	10/18/2011 to 7/13/2012	166.7	130	270	0
WQ03-2	10/16/2011 to 7/12/2012	170	130	271	0

Take "DH03-3" as an example, "DH" is a site, "03" is the subsite (specific land use) for DH, and "-3" is the duration between the 2nd and 3rd sampling date (detailed site information see Tables 2, 3); P is precipitation; I is irrigation amount; Δt is duration time; Δz is the downward movement of bromide concentration peak during a period time of Δt

Table 5 Recharge rates and coefficients calculated from tracer test data for all the locations

Study area	Location	Injection date	Sampling date	Δt (days)	Δz (cm)	θ	R (mm/a)	P (mm/a)	I (mm/a)	R_c
Piedmont plain	DH01	8/26/2010	10/22/2011	422	5	0.178	7.7	678.8	0.0	0.011
	DH03	8/26/2010	10/23/2012	789	155	0.171	122.6	666.7	210.5	0.140
	DH04	7/7/2012	10/23/2012	108	50	0.276	466.4	1263.0	439.4	0.274
	GY01	8/24/2010	10/22/2011	424	5	0.159	6.8	675.6	0.0	0.010
	GY02	8/24/2010	7/8/2012	684	180	0.255	244.9	570.8	416.2	0.248
	NC01	8/25/2010	7/6/2012	681	45	0.226	54.5	572.1	418.1	0.055
	LC01	8/27/2010	10/24/2012	789	185	0.227	194.3	666.7	30.1	0.279
	LC02	8/27/2010	7/8/2012	681	65	0.327	113.9	573.3	418.1	0.115
	LC03	7/8/2012	10/24/2012	108	45	0.283	430.4	1262.6	439.4	0.253
	LZ01	8/25/2010	10/25/2012	792	160	0.318	234.5	664.1	359.5	0.229
	LZ02	8/25/2010	7/6/2012	681	5	0.383	10.3	572.1	0.0	0.018
	DLZ01	9/4/2010	10/15/2012	772	85	0.274	110.1	467.4	430.2	0.123
	DLZ02	9/4/2010	10/15/2012	772	350	0.341	564.3	467.4	614.6	0.522
	DLZ03	9/4/2010	10/15/2012	772	45	0.175	37.2	467.4	92.2	0.067
Alluvial and lacustrine plains	XLT01	9/3/2010	10/20/2011	412	5	0.134	5.9	445.3	806.2	0.005
	XLT02	9/3/2010	10/20/2011	412	5	0.326	14.4	445.3	287.9	0.020
	XLT03	9/3/2010	7/14/2012	680	35	0.19	35.7	353.9	104.7	0.078
	XLT04	6/26/2011	10/20/2012	473	105	0.345	279.3	651.3	250.8	0.310
	WB01	7/4/2011	10/20/2011	108	5	0.339	57.3	980.4	219.7	0.048
	WB02	7/4/2011	7/15/2012	377	5	0.38	18.4	432.6	0.0	0.043
	WB03	7/12/2011	10/20/2011	98	5	0.329	61.3	1028.0	484.2	0.041
	DD03	9/5/2010	7/18/2012	682	75	0.368	147.7	407.9	347.9	0.195
	HC02	6/27/2011	10/12/2011	107	5	0.26	44.3	1108.6	0.0	0.040
	HC03	6/28/2011	10/22/2012	483	75	0.329	186.5	707.3	245.6	0.196
	HC04	6/28/2011	10/17/2011	111	15	0.358	176.6	1080.5	427.5	0.117
	HC05	2011/7/22	2012/7/16	360	25	0.319	80.9	492.8	304.2	0.102
	HC06	2011/7/22	2012/7/16	360	25	0.309	78.3	492.8	304.2	0.098
	HC07	2011/7/22	2012/7/16	360	20	0.297	60.2	492.8	76.0	0.106
	HC08	2011/7/22	2012/7/16	360	50	0.317	160.7	492.8	228.1	0.223
	HC09	2011/7/22	2012/7/16	360	55	0.278	155	492.8	152.1	0.240
	HC10	2011/7/22	2012/7/16	360	75	0.314	238.8	492.8	380.2	0.274
	ZW01	7/5/2011	10/12/2012	465	85	0.247	164.8	624.0	255.1	0.188
	ZW02	7/5/2011	10/13/2012	466	5	0.158	6.2	622.7	0.0	0.010
	ZW03	7/5/2011	10/13/2012	466	45	0.272	95.9	622.7	254.6	0.109
	WQ01	7/6/2011	10/12/2012	464	65	0.293	149.8	625.4	357.9	0.152
	WQ02	7/6/2011	10/12/2012	464	15	0.273	32.2	625.4	0.0	0.052
	WQ03	7/6/2011	10/12/2012	464	35	0.317	87.3	625.4	255.7	0.099

Take "DH03" as an example, "DH" is a site, "03" is the subsite (specific land use) for DH (detailed site information see Tables 2, 3); P is precipitation; I is irrigation amount; Δt is duration time; Δz is the downward movement of bromide concentration peak during a period time of Δt; θ is soil volumetric moisture content; R is recharge rate; R_c is recharge coefficient calculated by $R/(P + I)$

amounts of irrigation (130 mm) and no tracer transport was observed. In total, it can be concluded that precipitation alone was insufficient to promote tracer transport, and that significant transport was observed only for subsites with appreciable irrigation.

Recharge rates and recharge coefficients

The recharge rates (R) and recharge coefficients (R_c) calculated from the tracer data are presented in Table 5. Note that the irrigation at the 37 subsites mentioned above was applied by the landowners. Interviews with the landowners were taken to obtain an average value of irrigation amount that was 65 mm per irrigation event. The irrigation amount of the controlled irrigation study (HC05–HC10) was designated as 75 mm per irrigation event. For the piedmont plain sites, the recharge rates ranged between 37.2–466.4 mm per year (mm/a) (5.5–27.4% of precipitation plus irrigation, $P + I$) beneath wheat-maize, 110.1–564.3 mm/a (12.3–52.2% of $P + I$) beneath orchard, 6.8–10.3 mm/a (1.0–1.8% of $P + I$) beneath woodlands. Beneath woodlands for the alluvial/lacustrine plain sites, the recharge rates (except for the controlled irrigation study) ranged between 14.4–176.6 mm/a (2.0–19.5% of $P + I$) beneath wheat-maize, 5.9–57.3 mm/a (0.5–4.8% of $P + I$) beneath orchard, 87.3–279.3 mm/a (9.9–31.0% of $P + I$) beneath cotton, 6.2–44.3 mm/a (1.0–7.8% of $P + I$). The recharge rates and recharge coefficients are relatively small for non-irrigated or seldom irrigated sites, and larger for the more heavily irrigated sites (Table 5). The recharge rate and coefficient were largest for subsite DLZ02, which received the largest quantity of irrigation.

Recharge rates for different crop covers

The major crop covers in the study area were wheat-maize, cotton, poplar woods, and orchards. Figure 3 shows the recharge rates obtained for the different crop cover subsites for four sites. The recharge rates were very small for all the poplar subsites, because no irrigation was received and infiltration of precipitation is minimized by the presence of the trees. The largest recharge rate was observed for the grape subsite, 564.3 mm/a, as it received the largest irrigation amount (ten applications per year). Recharge rates varied moderately among the subsites with the same crop cover. For wheat-maize subsites, it was similar at ZW and WQ, all of which were in alluvial/lacustrine plain, with rates of 164.8 mm/a and 149.8 mm/a. For the DLZ site, the irrigation times for poplar woods, summer maize, pear orchard, and grape orchard were almost zero, once to twice, six times, and ten times per year, respectively. It is observed that the recharge rate for the pear orchard is significantly larger than that for the poplar woods. This difference, despite similarity of land covers, indicates the significance of irrigation in driving measured recharge rates.

Comparison of recharge rates under wheat-maize and under apple orchard

Two subsites with apple orchards serve as useful comparison locations to further investigate the impact of irrigation and crop cover on recharge. The DH03 subsite was irrigated normally before harvest time in 2011, after which no additional irrigation was received. The bromide concentration peak moved: downward 110 cm (see Fig. 4) between 26 August 2010 and 22 October 2011 (more than a complete hydrological year), downward 45 cm between 23 October 2011 and 7 July 2012 (with only one irrigation at the end of the year of 2011 and little precipitation), and minimally between 8 July 2012 and 23 October 2012 (no irrigation, but in the rainy season).

The LC site (Fig. 1) is now considered for further discussion. Figure 5 presents the bromide concentration distribution in the LC profile. The apple orchard subsite (LC01) (Fig. 5a) was irrigated once during the period from 27 August 2010 to 24 October 2011, after which no additional irrigation was provided. The peak of the curve was not captured by the first sampling date but could be inferred

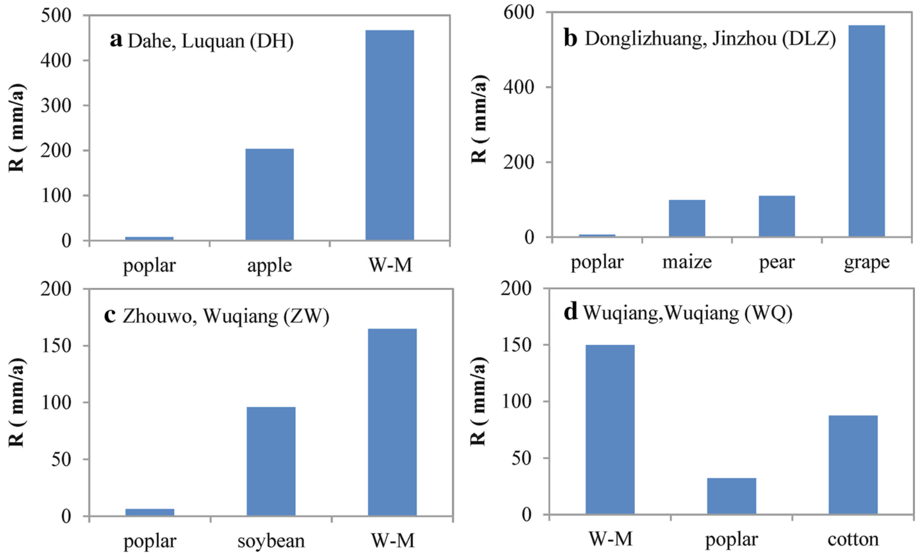

Fig. 3 Recharge rates (*R*) determined by tracer tests at different land use locations: **a** Dahe, Luquan (DH); **b** Donglizhuang, Jinzhou (DLZ); **c** Zhouwo, Wuqiang (ZW); **d** Wuqiang, Wuqiang (WQ). *Note* W-M is the short form for rotated winter wheat and summer maize

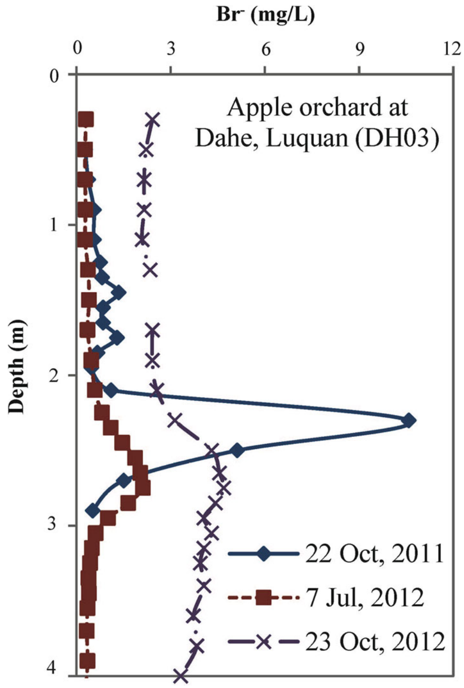

Fig. 4 Distribution of bromide concentration with depth at three dates for a saturated bromide solution applied at a depth of 1.2 m in an apple orchard at Dahe, Luquan (DH) at 26 August 2010. *Note* Since the bromide was applied, 390 mm irrigation and 785 mm rainfall was received before 22 October 2011, 455 mm irrigation and 1068 mm rainfall was received before 7 July 2012, and 455 mm irrigation and 1441 mm rainfall was received before 23 October 2012

by comparing the curve of 10 July 2012. The peak moved downward 185 cm from the injection date to the first sampling date. However, minimal movement was observed from 25 October 2011 to 10 July 2012 (dry season without irrigation) and from 11 July 2012 to 24 October 2012 (wet season without irrigation). These results indicate that tracer transport (recharge) was driven primarily by irrigation.

In comparison, the peak moved downward 20 cm from 27 August 2010 to 24 October 2011 (more than a complete hydrological year), and downward 45 cm during 24 October 2011 and 10 July 2012 (dry season) at the wheat-maize subsite (LC02) (Fig. 5b), which received standard irrigation. Specifically, the wheat-maize subsite was irrigated eight times during 27 August 2010 and 24 October 2011, compared to only once for the apple orchard subsite (LC01). However, the peak moved downward only 20 cm at wheat-maize subsite and downward 185 cm at apple subsite, with a recharge coefficient of 0.051 and 0.559 during this period, respectively. This indicates that wheat-maize farmland reduced infiltration of irrigation at LC site, which had a somewhat negative impact on groundwater management since the irrigation water is mainly pumped from groundwater.

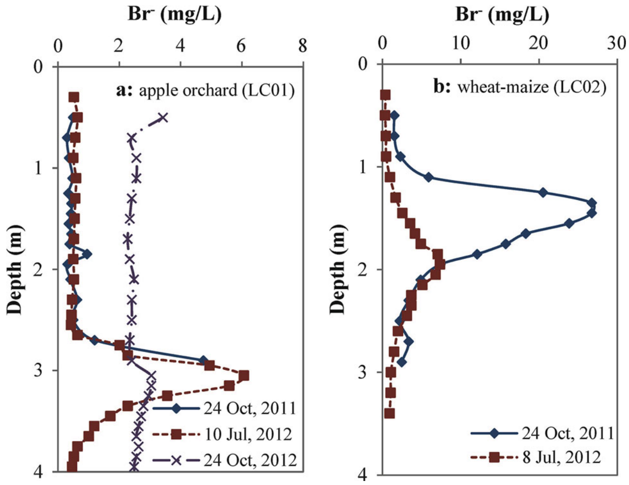

Fig. 5 Distribution of bromide concentration with depth for a saturated bromide solution applied at a depth of 1.2 m at Liangcun, Gaocheng (LC) at 27 August 2010: **a** in an apple orchard for three dates and only received 65 mm irrigation during 27 August 2010 and 24 October 2011; **b** in a rotated winter wheat and summer maize farmland for two dates and since the bromide was applied, 520 mm irrigation was received before 24 October 2011, and 780 mm irrigation was received before 8 July 2012

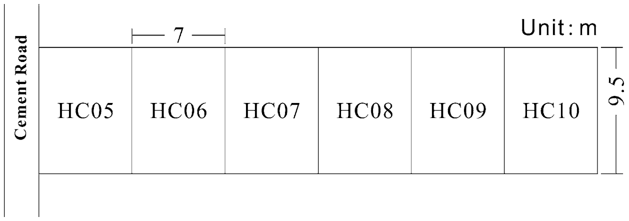

Fig. 6 Controlled experimental fields at Huchi, Shenzhou (HC) (map view)

Controlled irrigation experiment

The controlled irrigation experiment was conducted to investigate how irrigation amount impacted recharge. The experiments were conducted at six wheat-maize experimental fields (irrigated 75 mm per event) at Hebei Academy Dry-land Farming Institute, located at Huchi (HC), Shenzhou (SZ), Hengshui (HS) (Fig. 1). The test locations were in the center of each field, and the field next to the cement road (HC05) was regarded as the protective region which may impacted by the boundary. The map of the experimental field is presented in Fig. 6. Summer maize was irrigated once per year during the experimental period among the six different fields. Conversely, the irrigation amount was varied for winter wheat: thrice for HC05 and HC06 (which is considered the normal irrigation regime), none for HC07, twice for HC08, once for HC09, and four times for HC10.

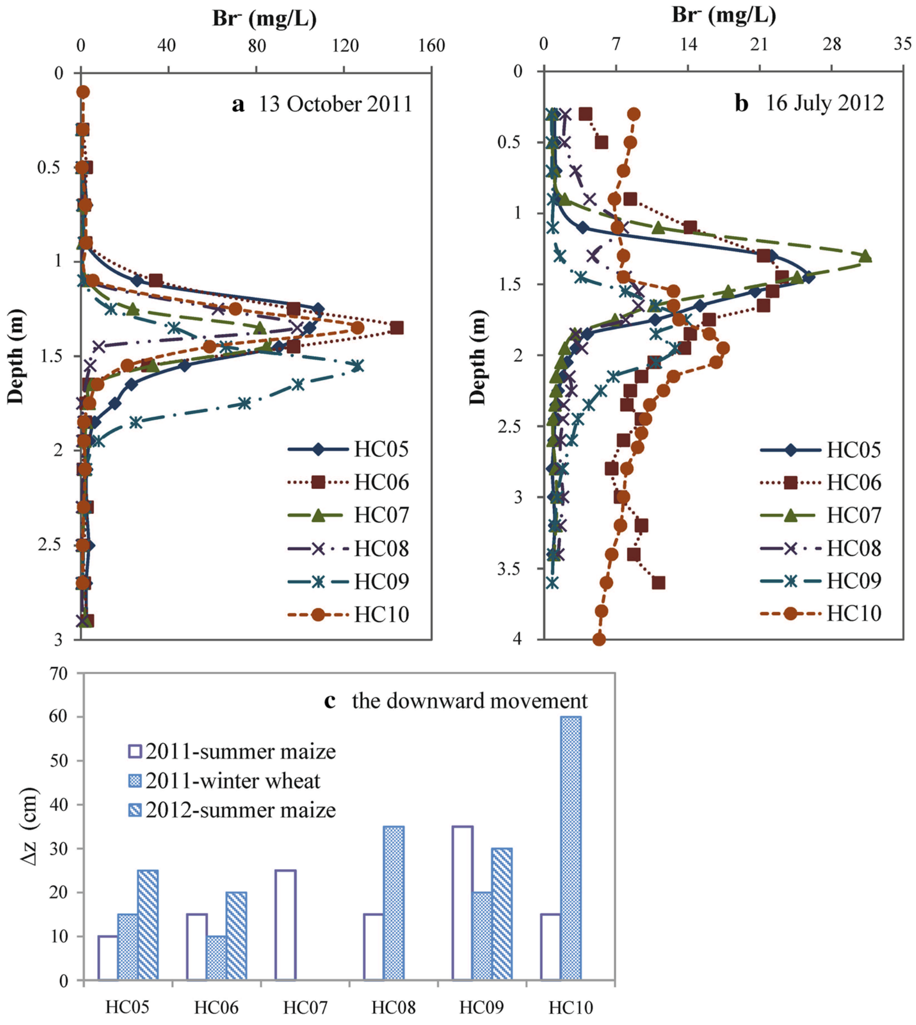

Fig. 7 Distribution of bromide concentration and downward movement of bromide concentration peak (Δz) at the controlled irrigation experimental subsite at Huchi, Shenzhou (HC) with rotated winter wheat and summer maize for a saturated bromide solution applied at a depth of 1.2 m at 22 July 2011: **a** the distribution of bromide concentration with depth at 13 October 2011; **b** the distribution of bromide concentration with depth at 16 July 2012; **c** the downward movement of bromide concentration peak during the growing seasons of summer maize and winter wheat. *Note* Detailed information for each location is presented in Tables 3, 5

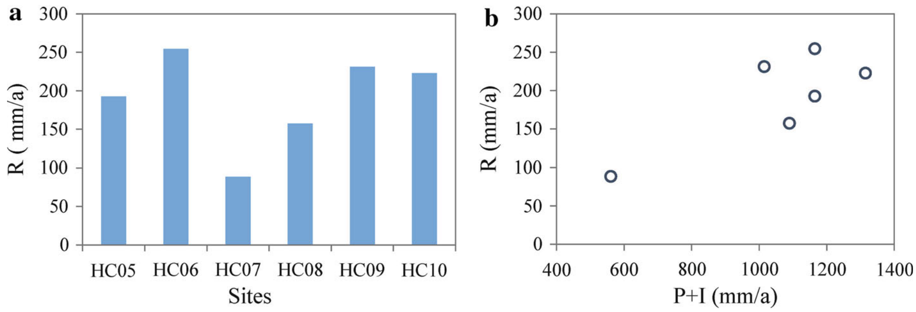

Fig. 8 Recharge rates (R) determined by tracer tests at the controlled irrigation experimental subsite at Huchi, Shenzhou (HC): **a** recharge rates at each location; **b** recharge rates as a function of irrigation plus precipitation amounts

The downward movement of the bromide concentration peak was larger during the wheat season than during the maize season for HC08 and HC10, opposite for HC07 and HC09, and similar for HC05 and HC06 (Fig. 7c). The downward velocity of the peak was almost the same during the maize season among the six locations, except for the once-irrigated field that had maximum peak movement, indicating the existence of preferential pathways (Fig. 7a).

In general, larger peak movement distances and associated recharge rates were obtained for the tests with larger rates of irrigation as would be anticipated (Figs. 7, 8) in a whole hydrological year, from 22 July 2011 to 16 July 2012. However, deviations from the anticipated behavior were observed, likely due to field-scale heterogeneity of hydraulic properties. For example, the recharge rate for the once-irrigated field was close to that observed for the thrice-irrigated field, and larger than that observed for the twice-irrigated field. Zhang et al. (1999) pointed out that grain yield of winter wheat was linearly related to seasonal evapotranspiration with a slope of 1.73 kg/m^3 in the piedmont of the NCP. To achieve the maximum grain yield, irrigation was 240 mm in the piedmont and was 195 mm (irrigated thrice if 65 mm per time) in the piedmont. Thus, irrigating thrice per season resulted in the highest water-use efficiency pattern. The controlled irrigation experiment also indicated that more irrigation would lead to a greater recharge rate. Thus, irrigating thrice times per season was sufficient to support crop growth while producing minimal recharge. If the crops were irrigated more than thrice, the excess water increased both recharge and evapotranspiration, which would negatively affect groundwater management.

Recharge differences between piedmont plain and alluvial and lacustrine plains

The vadose zone consists largely of sandy loam and loam at the piedmont plain with an average recharge coefficient of 0.167. It consists primarily of silt and clay at the alluvial and lacustrine plains with an average recharge coefficient of 0.119 (see Table 5). The recharge coefficients determined for sites within the piedmont plain were a little bit larger than those for sites within the alluvial and lacustrine plains. However, study results did not indicate that a coarser lithology would result in a larger recharge coefficient.

Comparison to prior research

Several recharge estimation efforts have already been conducted for the NCP, see Table 6. Most of the recharge rates and recharge coefficients obtained in this study are similar to those reported in the prior research (Kendy et al. 2004; Wang et al. 2008a, b; Liu et al. 2009; Lu et al. 2011; Tan 2012; Lin et al. 2013). The recharge coefficients of irrigated winter wheat–summer maize sites in the NCP in the previous study ranged from 0.072 to 0.240, which are similar to the current study with average recharge coefficients of 0.119 for the alluvial/lacustrine plain and 0.177 for the piedmont plain. In addition, recharge rates and recharge coefficients reported in the literature for sites within the piedmont plain were larger than those reported for alluvial/lacustrine plain sites, consistent with the results reported herein. Most of the previous research treated infiltration as piston flow, which resulted in smaller estimated recharge coefficients. Thus, some of the larger recharge rates obtained for the wheat-maize farmland likely is due to preferential flow. As a whole, the application of irrigation results in greater recharge in this study area. In addition, the recharge coefficients were the greatest in the irrigated wheat-maize farmland, followed by natural grass cover regions, and then the woodland sites.

Table 6 Previous groundwater recharge research for sites within the North China Plain

References	Sites (Fig. 1)	Method	Land use	R (mm/a)	R_c
Kendy et al. (2004)	Luancheng	1D soil–water-balance model	Irrigated cropland	5–109	–
Wang et al. (2008a)	Luquan	Applied ^{3}H	Irrigated wheat-maize farmland	171.6	0.226
	Luancheng	Applied ^{3}H & Br$^-$		190.7	0.215
	Shenzhou	Applied Br$^-$		131.4	0.139
Liu et al. (2009)	Zhengding	CMB & applied ^{3}H	Natural grass cover	89	0.167
Lu et al. (2011)	Luquan	Hydrus 1D	Irrigated wheat-maize farmland	169	0.210
	Luancheng			180	0.240
	Hengshui			140	0.210
Tan (2012)	the North China Plain	Applied Br$^-$	Mixed land use	105.7	0.155
		Infil 3.0		101.7	0.135
Lin et al. (2013)	Luquan	Modified CMB	Irrigated wheat-maize farmland	102.6	0.112
	Gaoying			65.9	0.072
	Gaocheng			126.8	0.139
	Luquan	CMB	Woodland	18.8	0.036
This study (average value)	Piedmont	Applied Br$^-$	Irrigated wheat-maize farmland	190.9	0.177
	Alluvial/lacustrine			147.9	0.119
	Piedmont		Woodland	21.1	0.013
	Alluvial/lacustrine			59.8	0.045

CMB is the short form for chloride mass balance; R is recharge rate; R_c is recharge coefficient calculated by $R/(P + I)$

Conclusions

1. The results showed that average potential recharge rate and coefficient were a little bit lower for the alluvial/lacustrine plain sites, which comprise finer-textured soils than those presented in the piedmont plain. For the piedmont plain sites, the potential recharge rate ranged between 37–466 mm/a (6–27% of $P + I$) beneath wheat-maize, 110–564 mm/a (12–52% of $P + I$) beneath orchard, and 7–10 mm/a (1–2% of $P + I$) beneath woodlands. For the alluvial and lacustrine plain sites, the potential recharge rate ranged between 14–177 mm/a (2–20% of $P + I$) beneath wheat-maize, 6–57 mm/a (0.5–5% of $P + I$) beneath orchard, 87–279 mm/a (10–31% of $P + I$) beneath cotton, and 6–44 mm/a (1–8% of $P + I$) beneath woodlands. The potential recharge rates obtained in this study may be used as input in a numerical modeling effort designed to simulate the regional groundwater flow in the NCP.
2. The potential recharge was impacted by various external factors, like lithology, crops, and irrigation. When an irrigation controlled experiment was conducted in the same field with the same crop cultivation, the results revealed that irrigation provided the primary contribution to recharge, with precipitation providing a minor contribution. Larger irrigation quantities led to larger recharge rates.
3. Overall, recharge was lower for the fields with the rotation cultivation of winter wheat and summer maize compared to the aged apple orchard.
4. In general, the irrigation quantity applied was larger than the requirement of the crops. Thus, managing the irrigation regime to insure that irrigation matches crop requirements would be helpful to better preserve groundwater resources and prevent water table decline.

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