Estimating groundwater recharge following land-use change using chloride mass balance of soil profiles: a case study at Guyuan and Xifeng in the Loess Plateau of China

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Abstract Groundwater recharge is affected by land use in (semi)arid areas. A new application of the chloride-mass-balance approach has been developed to estimate the reduction in groundwater recharge following land-use change by comparing chloride concentrations below the root zone and above the base of the chloride accumulation zone, before and after the land-use conversion. Two sites in the Loess Plateau of central China have been selected for study. Results from the Guyuan terrace region show that groundwater recharge beneath natural sparse small-grass was 100 mm/year, but the conversion to winter wheat about 100 years ago has reduced groundwater recharge to 55 mm/year. At the Xifeng Loess Plain the conversion from winter wheat, with groundwater recharge at 33 mm/year, to apple orchard 7 years ago has led to chloride accumulation to 5 m below land surface, suggesting the recharge rate has been reduced. This is in agreement with previous studies in these areas which have shown that the regional afforestation and other land-use conversions have resulted in deep soil desiccation and have caused an upper boundary to form with low matrix potential, thus preventing the soil moisture from actually recharging the aquifer.

Keywords Groundwater recharge/water budget · Unsaturated zone · Chloride mass balance · Land-use change · China

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Introduction

Groundwater is of fundamental significance for human development to meet the rapidly expanding urban, industrial, and agricultural water requirements, especially in (semi)arid areas (de Vries and Simmers 2002), and more than 2 billion people in the world depend on groundwater for their daily supply (Kemper 2004). Groundwater recharge is a key component in assessment of groundwater systems (Sanford 2002) and estimation of groundwater recharge is one of the most challenging issues in water resources research, which depends on lots of factors and is further complicated by environmental changes such as climate change (Maxwell and Kollet 2008; CCGS 2009), urbanization (Foster et al. 1994; Chilton 1999) and land-use change (Walker et al. 1991; Scanlon et al. 2007; Favreau et al. 2009).

Conventional water-balance methods and numerical unsaturated-zone simulations have been used to estimate groundwater recharge. However, they involve large errors in recharge estimation for (semi)arid areas (Gee and Hillel 1988). Furthermore, artificial tracers cannot give useful results during the short periods of measurement that are often used (Walker et al. 1991).

In order to gain better estimation of groundwater recharge in (semi)arid areas, hydrogeologists have made an effort to use environmental tracers such as tritium (Smith et al. 1970), chloride (e.g. chloride mass balance, CMB) (Allison and Hughes 1978; Edmunds et al. 1988), and chloride-36 (Phillips et al. 1988) in the unsaturated zone. Scanlon et al. (2006) presented a synthesis of global groundwater recharge estimation in (semi)arid areas and pointed out that the CMB technique is widely used and is an effective approach for estimating groundwater recharge.

However, groundwater recharge in (semi)arid areas is susceptible to land use/land cover. In Australia, removal of the indigenous vegetation more than 100 years ago significantly increased groundwater recharge and caused water-table rise (Allison et al. 1990). The water table in southwestern Niger has been rising in the past few decades (from 1963 to 2007 by 4 m) as a result of land clearing, with an increase in groundwater recharge from a previous 2–5 mm/year to the present 20–25 mm/year,

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despite a ~23% deficit in monsoonal rainfall from 1970 to 1998 (Leduc et al. 2001; Favreau et al. 2009). In the southern High Plains, Texas, southwestern United States, the conversion of natural grassland and shrubland ecosystems to rain-fed agriculture has displaced accumulated salinity from the unsaturated zone, indicating that the groundwater recharge has increased from almost zero to a median of 24 mm/year observed in 19 profiles (Scanlon et al. 2007). Therefore, groundwater recharge studies can provide valuable information for developing sustainable groundwater resource programs within the context of climate variability and land-use/land-cover change (Scanlon et al. 2006).

Water-level measurements, the most direct evidence of impacts of land-use change on groundwater recharge (Finch 2001; Favreau et al. 2002; Scanlon et al. 2005), cannot be used when a long-term groundwater level monitoring record is not available and when the groundwater level is affected by pumping, which can mask any impact of land-use changes (Scanlon et al. 2007). Moreover, when the unsaturated zone is very thick, it may take a long time for the moisture to reach the water table.

The unsaturated zone chloride profiles in (semi)arid areas can provide an archive of past climate change (Cook et al. 1992; Tyler et al. 1996; Edmunds and Tyler 2002) and land-use change (Rose et al. 1979; Allison and Hughes 1983; Jolly et al. 1989; Walker et al. 1991; Scanlon et al. 2007). Although the chloride mass balance can yield different recharge rates for different land-use scenarios, it takes considerable time to re-establish steady-state conditions following a land-use change. Before reaching a new equilibrium, the steady-state technique is invalid (Thorburn et al. 1990; Walker et al. 1991).

Some previous chloride studies have shown increased groundwater recharge as a consequence of land-use change. Jolly et al. (1989) showed the movement of pressure and solute fronts in response to long-term hydrological changes brought about by modification in land use. Rose et al. (1979) and Thorburn et al. (1990) developed a transient analysis of chloride profiles that were based on the chloride mass balance in the root zone. Increased recharge associated with land-use change results in downward displacement of the chloride bulge (Scanlon et al. 2007). Allison and Hughes (1983) developed the chloride front displacement (CFD) method to estimate the increased recharge rate. The CFD method relies on observation of the movement of a particular chloride pattern with depth which retains its shape during the leaching process (i.e. piston flow leaching). Assuming that a change in land use leading to increased vertical soilwater fluxes took place some years earlier, and that the flow is one-dimensional (1-D) and in the vertical direction, Walker et al. (1991) developed a generalization of the chloride front displacement (GCFD) technique, which did not assume piston flow leaching of chloride. However, both CFD methods provide only a lower bound on recharge rates for profiles where chloride is completely flushed (Scanlon et al. 2007).

The purpose of this study is to develop an approach for estimating the reduced groundwater recharge as a result of land-use change, using a comparative analysis of chloride profiles and chloride mass balance. The test sites are located in the Guyuan terrace region and the Xifeng Loess Plain, both of which are in the Loess Plateau of China.

Methodology

Chloride, one of the most common elements in groundwater, which only precipitates at very high concentrations, has been recognized as an ideal conservative tracer of water-cycle processes. The use of unsaturated-zone chloride profiles in recharge estimation was developed by Allison and Hughes (1978) in Australia and by Edmunds et al. (1988) in Cyprus. A conceptual model for the use of chloride to evaluate reduced groundwater recharge following a land-use change is illustrated in Fig. 1. The input of chloride to the unsaturated zone is from precipitation ($P \times C_\mathrm{p}$, where C_p is the mean chloride in precipitation) and the net dry deposition (D). Chloride will be transported through the upper soil zone during the rainy season at rates depending on the rainfall intensity and will become concentrated as a result of evapotranspiration (E). The chloride concentration and moisture in the root zone (from surface to Zr) will vary seasonally or annually depending upon the intensity of the moisture flux due to the incident rainfall and evapotranspiration as the plants exclude chloride during water uptake. Only chloride concentrations (C_S) below this depth represent that of recharge water. The water percolating into the unsaturated zone below root zone is referred as *potential recharge* (deep drainage) since it is unlikely to be removed upward to the surface, so as to distinguish it from *actual recharge*. In the following discussion, potential recharge is labeled simply as recharge for brevity.

Assuming that the only source of chloride is from the soil surface, either by rainfall or dry deposition, and that there is no contribution of chloride from weathering, the surface runoff is negligible, and the 1-D vertical steady-state chloride flux is tenable (Fig. 1a), the recharge rate is given by (Allison and Hughes 1978; Edmunds et al. 1988)

$$\mathrm{R} = \frac{P \cdot C_\mathrm{P} + D}{Cs} \tag{1}$$

Following a land-use change, which leads to decrease in groundwater recharge (Fig. 1b), the only factor is the increased evapotranspiration of the vegetation. Before a new equilibrium is established, the decreased recharge will lead to a zone of chloride accumulation within certain depth ranges. Assuming that there is a depth, Zb, at which the chloride concentration remains at the value of old land use, the chloride contents above Zb represent new land use, and below Zb represent old land use. When steady-state conditions under the new

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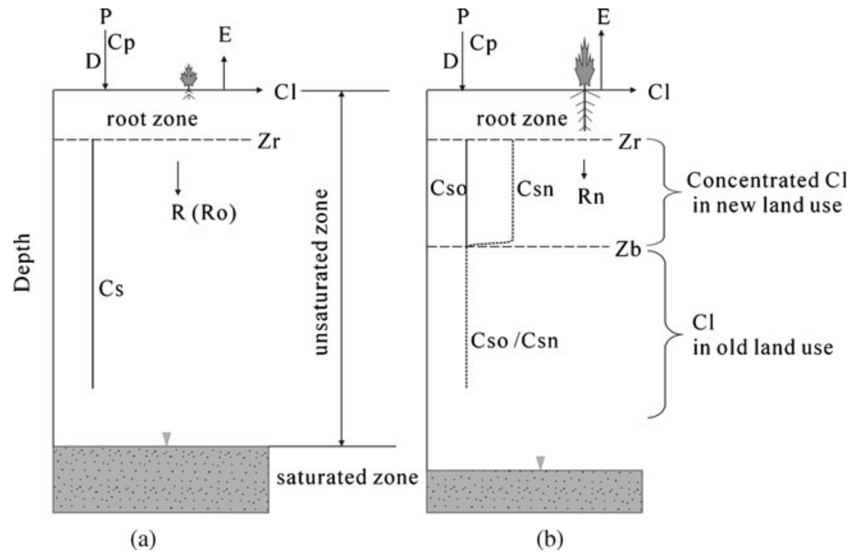

Fig. 1 Schematic representation of chloride concentration changes following land-use change. **a** Before and **b** after land-use change. The *symbols* are defined in the text

land use has been established above Zb and below Zr, the change in groundwater recharge is given by

$$\Delta R = R_n - R_o = (P \cdot C_P + D)\left(\frac{1}{C_{Sn}} - \frac{1}{C_{So}}\right) \quad (2)$$

and the relative change is given by

$$\frac{R_o - R_n}{R_o} = 1 - \frac{C_{So}}{C_{Sn}} \quad (3)$$

where R_o is recharge rate under the condition of old land use and R_n is recharge rate under new land use, C_{So} is the average chloride concentration in old land use above the depth of Zb derived from comparison with the new land use, and C_{Sn} is the average chloride concentration in new land use above Zb, respectively.

The average chloride concentration (C_S) in the concentrated zone is given by

$$C_S = \frac{\int_{Zr}^{Zb} \theta v(z) \cdot C_S(z)dz}{\int_{Zr}^{Zb} \theta v(z)dz} \quad (4)$$

where θv is volumetric moisture content.

The main limitation of the chloride mass balance is the uncertainty of chloride input. Edmunds et al. (1988) suggested that a 3 or 4 year spatially averaged value may be adequate but ideally there should be supporting evidence to indicate that this value is representative of a much longer time period. Assuming a 20% error in the chloride input estimation, and about 10% error in the soil chloride concentration, and that a new chloride equilibrium has been established for the new land use, then the total error for the absolute change of groundwater recharge derived from Eq. (2) is 23% $\left(\sqrt{(20\%)^2 + (10\%)^2}\right)$, and the relative change derived from Eq. (3) is 10% due to the same chloride input.

Application to loess profiles at Guyuan and Xifeng

Site description

Loess covers about 10% of the Earth′s land surface and is mainly distributed in temperate climates and semiarid climates on the edge of deserts, where the population is dense and industry/agriculture is highly developed. Chinese loess is mainly distributed in the middle reaches of the Yellow River (Fig. 2), accounting for about 72% of loess-covered area (0.44 million km^2) in China (Liu 1985). Loess is an aeolian sediment, and is homogeneous, porous, friable, slightly coherent, typically nonstratified and often calcareous. The silt particle content of loess accounts for a significant proportion (50–80%); loess is composed of quartz, feldspar, mica and other minerals and enriched in carbonate (typically up to 10–15% or higher; Liu 1985).

The first study site, Hequan in Guyuan City, is located in the east of the Liupan Mountain, and is a rain-fed agricultural terrace area with the main crop of winter wheat. The average precipitation from 1957 to 2008 at Guyuan Meteorology Station was 450 mm/year, and the average temperature was 6.6°C. About 60% of annual precipitation falls between July and September. The clayey sand and gravel is covered by the upper Pleistocene (Malan Loess, Q_3) in Hequan (Fig. 3).

The Xifeng Loess Plain is located in the central Loess Plateau of China with the maximum loess depth of ~200 m and with an area of 910 km^2, and is a typical rain-fed agricultural area (Fig. 3). The main crops are winter wheat and corn. The average precipitation from 1951 to 2008 at Xifeng Meteorology Station was 523 mm/year, and the average temperature was 8.5°C. The horizontal Neogene/Cretaceous mudstone and sandstone

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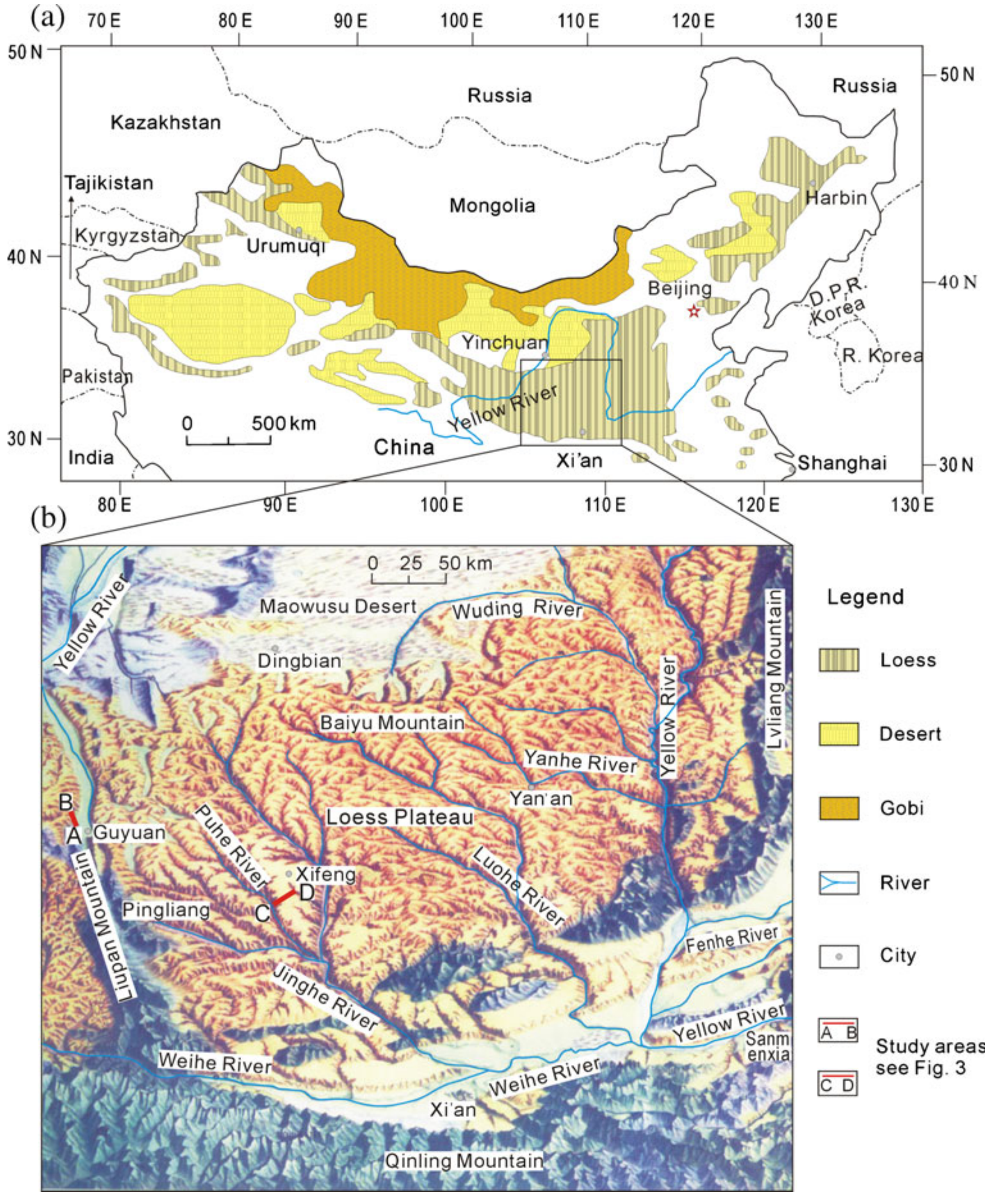

Fig. 2 **a** Loess distribution in China (modified from Liu 1985), and **b** the topography of the study area (modified from Hou and Zhang 2004)

beds are covered by Quaternary loess (Hou and Zhang 2004). The Quaternary loess is comprised of lower Pleistocene (Wucheng Loess, Q_1), middle Pleistocene (Lishi Loess, Q_2), and upper Pleistocene (Malan Loess, Q_3). The Wucheng Loess, with a thickness of 40–60 m, commonly crops out at the bottom of the upper and middle reaches of gullies. The hard and compacted Wucheng Loess has low permeability and is usually considered as an aquitard. The Lishi Loess has a thickness of 120–150 m, and commonly crops out on the sides of valleys and at the heads and cliffs of gullies. The Lishi Loess is unconsolidated and has relatively large porosity, and is considered to be a good aquifer. The Malan Loess has a thickness of 10–15 m, and is distributed above the Lishi Loess, as the top soil in the area, though the Holocene Loess is present in some cases.

In the Xifeng Loess Plain, the regional groundwater flow is from north to south. The depth of the water table ranges from 30 to 85 m with an increasing trend from the centre of the plain to its surrounding. The discharge of groundwater is mainly in the form of 'suspension' gravity springs in gullies (Qu 1991). Under the impacts of anthropogenic activities, the significantly increased pumpage has caused the regional water table to decline dramatically (2 m/year; Fig. 4). The previous studies used conventional water-balance methods and concluded that the ratio of groundwater recharge to precipitation is 6.7% in the Xifeng Loess Plain (Qu 1991). Studies of groundwater recharge using environmental tracers in the (semi) arid areas of China are relatively rare; the only available references focus on Badain Jaran Desert (Ma and Edmunds 2006; Gates et al. 2008) based on chloride

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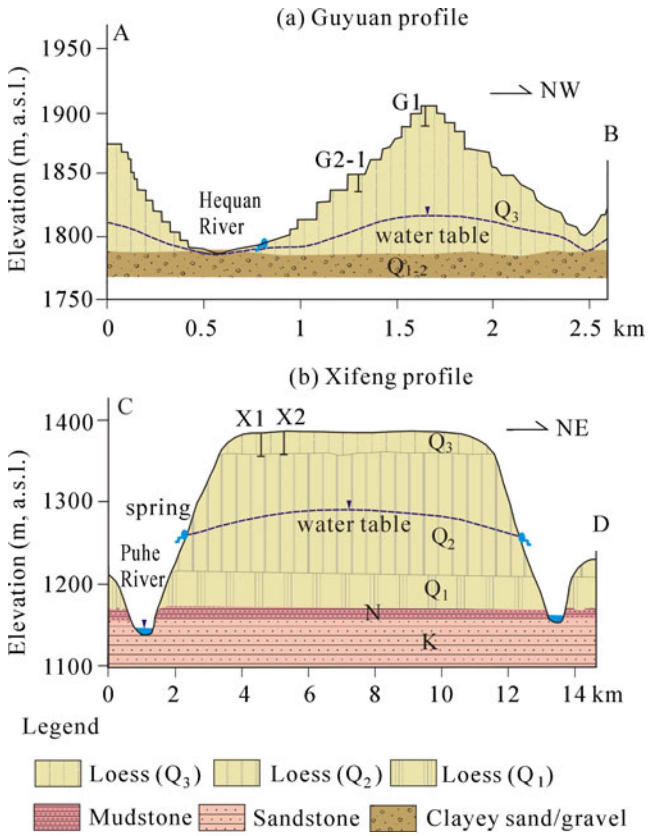

Fig. 3 **a** The Hequan hydrogeological profile in Guyuan (A–B) and **b** the Xifeng hydrogeological profile (C–D; derived from Qu 1991)

profiles, loess-covered areas in the Shanxi and eastern Inner Mongolia areas based on tritium profiles (Lin and Wei 2006), and the North China Plain based on chloride profiles (Chen et al. 2001) and artificial tritium and bromide (Wang et al. 2008).

Three possible sources of chloride in groundwater have to be considered in every case study: rock salt, seawater and sea-derived airborne salts. For all fresh groundwater types, the rock-salt source (halite, shale, clay) for chloride can be ruled out (Mazor 2004). There are no rock salt and seawater sources in the unsaturated zone with respect to the present chloride. Even though there was a little depositional chloride when the loess was formed in some cases, the subsequent precipitation had flushed it into groundwater. In well-drained soil, this appears to be a reasonable approximation (Allison and Hughes 1978). Therefore, the only source of chloride is from the soil surface, either in rainfall or dry deposition ($P \times C_p + D$). If there are other chloride sources at the surface, they should be added to the total chloride inputs flux, e.g. possible fertilizer. The chloride input flux has excluded the chemical fertilizers used in the area, in which there is little chloride. If the volume-weighted average chloride concentration in rainfall of 1.7 mg/L (from 2001 to 2007) for a rural monitoring station in the vicinity of Xi'an, China (EANET 2009), and the value of 1.7 mg/L measured by Xu et al. (2009) in Lanzhou (both in the Loess Plateau of China) are adopted due to the lack of observation in the study areas, and the aerosol flux deposition is negligible (which is acceptable provided the long-term aerosol flux is near steady state, Goni et al. 2001), then the annual chloride input from the atmosphere is expected to be 765 mg/m^2/year (450 mm/year × 1.7 mg/L) for Guyuan and 889 mg/m^2/year (523 mm/year × 1.7 mg/L) for Xifeng. The chloride input from possible manure fertilizer (~5 g NaCl for one person per day) to cultivated land in the study areas is within the error of atmospheric deposition (10–15%) and then is ignored.

In a homogeneous unsaturated zone, soil water moves down mainly by piston flow (Zimmermann et al. 1967). The loess, including the paleosol is unconsolidated, and the homogeneous porosity suggests that no significant preferential flow occurs in the loess deposition area, except near the cliffs and gullies. The obvious 1963 tritium-peak in the unsaturated zone in the loess-covered region (Baran et al. 2007; Lin and Wei 2006) confirmed the existence of piston flow in loess. The chloride mass balance is feasible for estimating groundwater recharge in the areas.

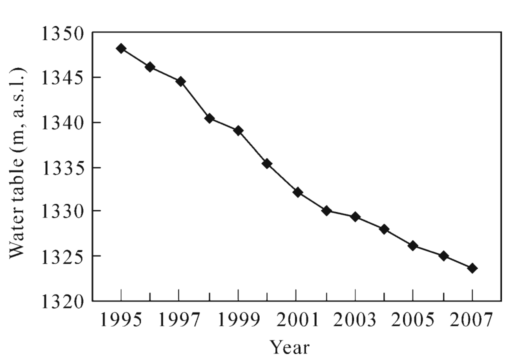

Fig. 4 Water-table changes from 1995 to 2007 for the China Geological Survey borehole 6228010043 near the soil sampling sites in the Xifeng Loess Plain

Soil sampling and analyses

Soil samples were collected from two sampling profiles in Guyuan and two in the Xifeng Loess Plain in August 2009. The two soil profiles in Guyuan are G1 (depth of 14.25 m, natural ecosystem of sparse small-grass) and G2-1 (depth of 11.25 m, more than 100-year-old winter wheat field, which had previously been natural ecosystem). In the Guyuan study area, profile G1 is used for presenting the starting land-use profile. One soil profile (X1, depth of 14.5 m) in Xifeng was taken in a winter wheat field and the other (X2, depth of 15 m) was in a 7-year-old apple orchard which had previously been a winter wheat field. The profile X1 can be used to provide the starting or old land-use profile for comparison with the converted apple orchard.

The soil samples were obtained using a hollow-stem hand auger with interchangeable 1.5-m aluminum rods. Bulk soil samples of ~400 g were collected at an interval of 0.25 m. Samples were immediately sealed in polyethylene bags. The magnetic susceptibility (MS) of sediments (10 g) was measured on a Bartington MS2 system to distinguish the loess from paleosol, which reflects the

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sedimentary environment. The particle size was measured on a Shimadzu SALD-3001 laser particle analyzer. Gravimetric moisture content was determined by drying a minimum of 80 g of soil sample at 110°C for 12 h. To determine chloride content, double-deionized water (40 ml) was added to the oven-dried soil sample (40 g). Samples were agitated on a reciprocal shaker table for 8 h. The supernatant solution was filtered through 0.45-μm filters. Chloride was then analyzed by ion chromatography. The chloride concentration of the soil solution is then calculated by dividing the measured concentration by gravimetric moisture content and by multiplying the mass ratio of solution over oven-dry soil. Chloride concentration was measured using ion chromatography (Dionex-500) at the Beijing Research Institute of Uranium Geology. The methods for anion measurements are taken from the National Analysis Standard DZ/T0064.51-93. Analytical precision was 3% of concentration based on reproducibility of samples and standards, and detection limit was 0.1 mg/L.

Results and discussion

Sediments and moisture content

The soil sediments can be classified as loess and paleosol due to different sedimentary environments (An et al. 1991). The paleosol always has a higher magnetic susceptibility (MS) and finer particle size than the loess (Table 1). Figures 5 and 6 illustrate the MS and moisture content for the four soil profiles. Guyuan sampling sites are all Malan Loess (L_1, the terms are defined in Table 1). The cultivated soils near the surface have relatively high MS (reaching 100×10^{-8} m^3/kg) for profiles G2-1, X1 and X2. The Holocene soil with high MS has been denuded in profile X1 but occurs in profile X2 (depth 0.5–2 m). The two soil profiles in Xifeng all have one paleosol in Malan Loess (7–8 m for profile X1 and 9–10 m for profile X2) and the paleosol (S_1) in Lishi Loess. As a whole, the sedimentary depth of profile X2 is 2 m lower than that of profile X1. Since a paleosol with high MS has finer particle size than a loess, and can hold more moisture, the moisture in a paleosol is relatively higher than in a loess in the most cases. In the upper part of the profiles the moisture is lower due to evapotranspiration in the dry season. The moisture contents above 0.75–1.00 m were affected by large rainfall events before sampling for the four profiles. At the top of the paleosol S_1, the gravimetric moisture contents reach a maximum of 23.7% and 23.2% for profile X1 and X2, respectively, which is the field capacity for these soils.

Chloride profiles and implications for changing recharge

The Cl concentration above 0.25 m is as low as 7.9 and 3.9 mg/L for profiles X1 and X2, respectively, due to a large amount of rainfall dilution before sampling (Fig. 7). All four profiles exhibit a peak of Cl concentration in the root zone. The presence of a chloride peak is widespread in (semi)arid areas, which has been shown in numerous localities world-wide (Ma and Edmunds 2006; Gates et al. 2008; Scanlon 1991; Phillips 1994). Removal of moisture near the surface by evapotranspiration contributes to the accumulation of solutes. The high chloride in the root zone (1.50–1.75 m for G1 and G2-1, 0.75–1.25 m for X1 and X2) may also be due to some mineralization. The moisture locally bypasses zones where chloride is occluded in closed pore spaces which are accessed by the centrifuge/elutriation techniques but not during recharge, as discussed in detail in earlier studies from Cyprus and Senegal (Edmunds et al. 1988; Edmunds and Gaye 1994).

The chloride concentrated by evapotranspiration generally remains in the root zone until it is flushed downward below the root zone (below 2 m in this case) by infiltrating precipitation. The average chloride concentration below the

Table 1 Particle size and magnetic susceptibility (*MS*) for part of soil samples from G2-1 in Guyuan and X2 in Xifeng. S_0 Holocene loess; L_1 upper Pleistocene loess; L_1S paleosol in upper Pleistocene loess; S_1 first layer of paleosol in middle Pleistocene loess

Sample no.	Depth (m)	Soil type	Size <2 μm (%)	Size 2–50 μm (%)	Size 50–2,000 μm (%)	Median particle size (μm)	MS (10^{-8} m^3/kg)
G2-1-3	0.50~0.75	L_1	17	65	18	19	94
G2-1-6	1.25~1.50	L_1	17	66	17	19	51
G2-1-10	2.25~2.50	L_1	14	67	19	22	31
G2-1-21	5.00~5.25	L_1	15	68	17	21	39
G2-1-31	7.50~7.75	L_1	15	72	13	17	54
G2-1-45	11.00~11.25	L_1	17	74	9	14	47
X2-1	0.00~0.25	Cultivated soil	16	70	14	18	105
X2-2	0.25~0.50	S_0	16	70	14	20	76
X2-6	1.25~1.50	S_0	20	71	9	10	171
X2-11	2.50~2.75	L_1	11	74	15	22	54
X2-19	4.50~4.75	L_1	11	73	16	24	40
X2-29	7.00~7.25	L_1	16	76	8	15	80
X2-37	9.00~9.25	L_1S	14	77	9	17	102
X2-41	10.00~10.25	L_1	15	73	12	18	57
X2-46	11.25~11.50	L_1	16	73	11	16	36
X2-54	13.25~13.50	S_1	18	74	8	13	126
X2-57	14.00~14.25	S_1	19	75	6	11	175

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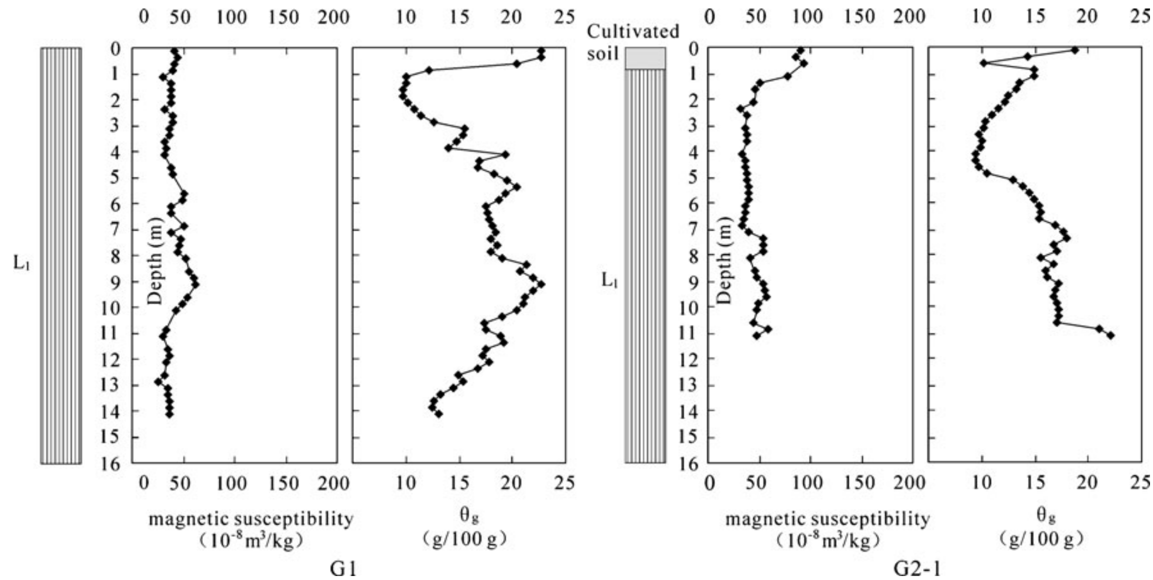

Fig. 5 The loess series (L) in the profiles *G1* and *G2-1* in Guyuan, showing magnetic susceptibility and moisture content (θ_g)

root zone (below 2 m) for G1 (natural ecosystem) is 7.7 mg/L. The groundwater recharge rate beneath the natural ecosystem is 765/7.7=100 mm/year based on the chloride mass balance, accounting for 22% of annual precipitation. The conversion from the natural ecosystem (G1) to winter wheat (G2-1) more than 100 years ago had led to chloride concentration below the root zone to an available depth of 11.25 m. The average chloride concentration below the root zone is 13.9 mg/L (typically ranging from 7.9 to 24.9 mg/L) for G2-1. If the chloride input-flux is stable and preferential flow is insignificant, the variance of Cl concentrations in the unsaturated zone reflects the climate changes or recharge rate change (Cook et al. 1992). The steady-state condition beneath the more than 100-year-old winter wheat farm seems to be established; the groundwater recharge rate beneath winter wheat is 765/13.9=55 mm/year. The conversion resulted in the decrease in groundwater recharge by 45%.

Below the root zone, Cl concentration for X1 fluctuates generally within a range of 13.4 to 64.8 mg/L with an average of 27.3 mg/L by weight (Fig. 7), assuming that the soil bulk density for loess is 1.4 g/cm^3 and for paleosol is 1.5 g/cm^3. The groundwater recharge rate in winter wheat is estimated to be 889/27.3=33 mm/year (about 6.3% of annual average precipitation of 523 mm/year,

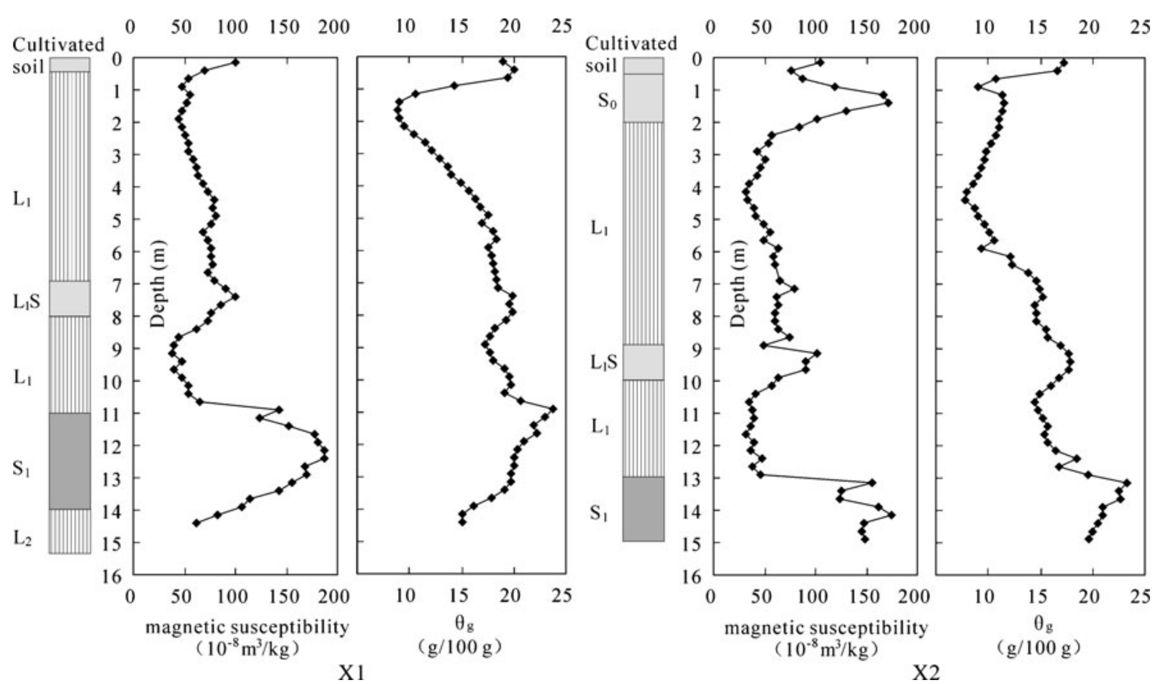

Fig. 6 The loess-paleosol series (L and S) in the profiles *X1* and *X2* in the Xifeng Loess Plain, showing magnetic susceptibility and moisture content (θ_g)

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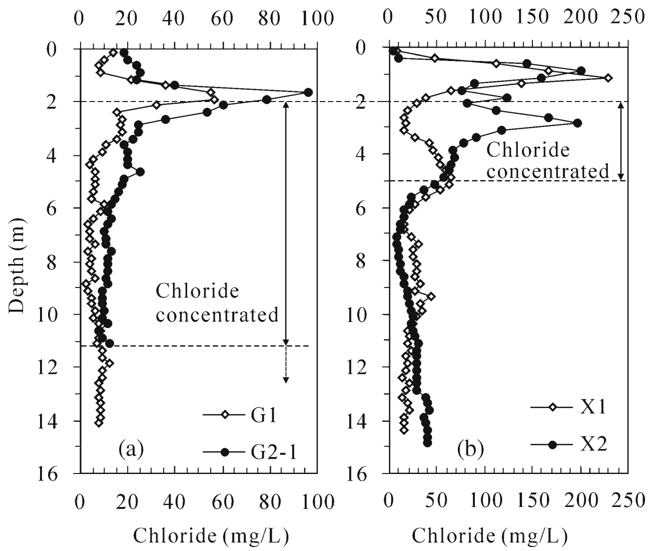

Fig. 7 Chloride concentration profiles for **a** G1 and G2-1 in Guyuan, and **b** X1 and X2 in the Xifeng Loess Plain

similar to 6.7% obtained by Qu (1991) using water mass balance).

Profile X2 exhibits similar characteristics of chloride concentration compared to profile X1, except in the depth ranging from 2 to 5 m (Fig. 7). The conversion from winter wheat to a high-water-use apple orchard 7 years ago has led to soil-water depletion and chloride accumulation. From 2 to 5 m, the depletion of moisture for the apple orchard is 186 mm as compared to the winter wheat field. The average chloride concentration in the winter wheat field is 39.1 mg/L between 2 and 5 m, whereas in the apple orchard it is 99.2 mg/L. As the profile is comprised of predominantly silt and clay, leaching and accumulation of chloride in the profile would be a slow process. The apple orchard would accumulate chloride further. For example, chloride concentration is typically 350–400 mg/L below the root zone for a 20-year-old apple orchard (C. Li, Lanzhou University in China, personal communication, 2010). As the chloride mass balance only works if the chloride in the zone above Zb and below Zr has come to a new equilibrium, the actual decrease in groundwater recharge cannot be estimated using chloride mass balance. However, it can be concluded that the moisture does not actually reach the zone below Zb (5 m) and chloride would be further accumulated in the next few years till the new steady state is established. At that point, moisture with accumulated chloride could reach the zone below Zb with a decreased recharge rate.

Implications for water-resources management

The Loess Plateau of China is one of the most severely soil-eroded areas in the world. Over 60% of the land in the Loess Plateau has been subjected to soil and water loss (Yang and Yu 1992) and the sediment load of the Yellow River has 9–21 times more solid particle content than that of most major rivers in the world (Shi and Shao 2000). Since the 1950s, governments began soil and water conservation practices in order to control the soil erosion and increase the productivity of crops. However, since the 1980s, soil desiccation has occurred, as a result of the introduction of trees or alfalfa and a long-term low rainfall period (Chen et al. 2008; Li and Huang 2008). The water deficit caused by increased evapotranspiration prevents gravitational infiltration of water and the replenishment of groundwater (Li 2001). Studies from selected catchments in the Loess Plateau of China following large-scale soil-conservation measurements show decreases in annual stream flow (Mu et al. 2007; Zhang et al. 2008).

This study shows the decrease in groundwater recharge when the vegetation is converted to a type with higher water demands. The local governments want to develop apple orchards to increase the income of farmers in most areas of the Loess Plateau of China. Some apple trees older than 30 years have been removed and the crop has been converted to winter wheat; wheat planted after apple trees suffers from low yield, and groundwater suffers from a low recharge rate due to the reduced soil-water content (Huang and Gallichand 2006). Application of a 1-D simulation model (simultaneous heat and water transfer) shows that that the recovery time varies from 6.5 to 19.5 years, with an average of 13.7 years, for a 10-m soil profile (Huang and Gallichand 2006). The regional afforestation and other land-use conversions, which could result in deep soil desiccation and form the upper boundary with low matrix potential, prevent the moisture from infiltrating and then recharging the aquifer. This does not appear to be favorable to the groundwater resources, and could accelerate depletion of the soil reservoir in the Loess Plateau of China, counteracting the regional eco-environment reconstruction efforts.

Conclusions

Reduced groundwater recharge caused by land-use change can be estimated by comparing the chloride concentration in the soil water from the base of the root zone to the base of the chloride-concentrated zone, for pre-converted and converted land uses, based on the chloride mass balance and using the unconverted land use as the background for comparison.

Soil profiles from Guyuan show that the groundwater recharge beneath sparse small-grass was 100 mm/year, and the conversion to winter wheat more than 100 years ago has resulted in reduced groundwater recharge, to 55 mm/year. At Xifeng, the conversion from winter wheat (with the recharge rate of 33 mm/year) to apple orchards 7 years ago has led to chloride being concentrated in the soil profile from land surface to about 5 m depth, suggesting the recharge rate has decreased.

Strong water-resources implications for the Loess Plateau of China lie in the fact that regional afforestation and other land-use conversions to vegetation with higher water demand may have caused soil-water depletion and

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solute concentration, and are, therefore, not favorable to groundwater recharge and ecosystem restoration.

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