Estimating groundwater recharge in a cold desert environment in northern China using chloride

John B. Gates · W. M. Edmunds · Jinzhu Ma · Bridget R. Scanlon

Abstract Understanding sources and rates of recharge to the Badain Jaran Desert in northern China is important for assessing sustainability of the area's oasis lake ecosystem and its water resources in general. For this purpose, direct recharge was investigated with the chloride mass balance method for 18 unsaturated zone profiles (6–16 m depth). Spatial variability is low across the area (range in mean Cl in profiles: 62–164 mg/L Cl), largely attributable to the uniformity of sandy unsaturated zone conditions. No strong correlations between environmental factors of profile locations and recharge rates were found, though a weak relationship between recharge and vegetation density was suggested. The study area's complex dune morphology appears to have no measurable impact on recharge variability. Mean estimated diffuse recharge is 1.4 mm/year (1.0–3.6 mm/year for 95% confidence level), approximately 1.7% of mean annual precipitation. Temporal fluctuations in recharge due to climate variability are apparent and there is good correspondence in temporal trends over a time span of 200–300 years. Water balance considerations indicate that direct recharge is insufficient to support the numerous perennial lakes in the study area, suggesting that diffuse recharge presently plays a minor role in the overall water balance of the desert's shallow Quaternary aquifer.

Received: 5 March 2007 / Accepted: 6 December 2007
Published online: 1 February 2008

© Springer-Verlag 2007

J. B. Gates (✉) · W. M. Edmunds
Oxford Centre for Water Research,
Oxford University,
Oxford, OX1 3QY, UK
e-mail: john.gates@beg.utexas.edu

J. Ma
Center for Arid Environment and Palaeoclimate Research,
Key Laboratory of Western China's Environmental System,
Lanzhou University,
Lanzhou, 730000, China

B. R. Scanlon
Bureau of Economic Geology, Jackson School of Geosciences,
University of Texas at Austin, University Station,
Box X, Austin, TX 78713-8924, USA

Résumé Comprendre les origines et les taux de la recharge du désert de Badain Jaran dans le Nord de la Chine est important pour estimer la durabilité des écosystèmes de la zone, écosystème de lacs et d'oasis, et ses ressources en eau en générale. Pour cela, la recharge directe a été étudiée via la méthode de la balance des chlorures sur 18 profils de la zone non-saturée (6–16 m de profondeur). La variabilité spatiale est faible sur la zone d'étude (Le Cl moyen par profil variant de 62–164 mg/L), variabilité largement attribuée à l'uniformité de l'environnement sableux de la zone non-saturée. Des corrélations fortes entre les facteurs environnementaux localisés autour des profils et les taux de recharge n'ont pas été trouvés, tandis qu'une relation faible entre la densité de la recharge et la végétation est suggérée. La morphologie dunaire complexe semble avoir un faible impact sur la variabilité de la recharge. La recharge diffuse moyenne est de 1.4 mm/a (1.0–3.6 mm/a avec un intervalle de confiance de 95%), soit approximativement 1.7% de la précipitation moyenne annuelle. Les fluctuations temporaires de la recharge, dues à la variabilité climatique sont apparentes et il existe une bonne tendance temporaire sur une période de 200–300 ans. Les considérations sur la balance en eau indiquent que la recharge directe est insuffisante pour supporter les nombreux lacs permanents de la zone d'étude, suggérant que la recharge diffuse actuelle joue un rôle mineur dans la balance en eau globale de l'aquifère phréatique Quaternaire.

Resumen Comprender las fuentes y tasas de recarga en el Desierto de Badain Jaran, en el norte de China, es importante para la sostenibilidad del ecosistema del oasis lacustre y sus recursos de agua en general. Con este propósito, la recarga directa fue investigada con el método del balance de masa de cloruro en 18 perfiles en zona no-saturada (6–16 m de profundidad). La variabilidad espacial es baja a través del área (intervalo de Cl promedio en los perfiles: 62–164 mg/L Cl), mayormente atribuible a la uniformidad de condiciones arenosas en la zona no-saturada. No se encontraron correlaciones fuertes entre los factores ambientales en los sitios de los perfiles y las tasas de recarga, aunque los resultados sugieren una relación débil entre recarga y densidad de vegetación. La compleja morfología de duna en el área de estudio parece no tener impacto medible sobre la variabilidad de recarga. La recarga difusa promedio estimada es 1.4 mm/año (1.0–

 DOI 10.1007/s10040-007-0264-z

3.6 mm/año para el 95% de nivel de confianza), aproximadamente el 1.7% de la precipitación media anual. Las fluctuaciones temporales en la recarga debidas a variabilidad del clima son aparentes y hay una buena correspondencia en patrones temporales en un periodo de 200–300 años. Consideraciones del balance hídrico indican que la recarga directa es insuficiente para explicar los numerosos lagos perennes en el área de estudio, sugiriendo que la recarga difusa juega actualmente un papel menor en el balance hídrico total del acuífero Cuaternario somero del desierto.

Keywords Groundwater recharge · Unsaturated zone · Arid regions · Chloride mass balance · China

Introduction

Desert hydrological systems represent an intricate balance between climatic forcing and hydrosphere/biosphere interactions. Understanding the roles of the various components of the system is important for assessing potential impacts of natural or anthropogenic perturbations on groundwater. One key aspect is the delineation of recharge pathways and rates, as groundwater response to environmental change is heavily dependent upon their characteristics. For example, many arid regions (e.g. Australia, southwestern US) have experienced little or no direct recharge (≤~0.01 mm/year) for millennia, building up salts in the unsaturated zone over these timescales (Allison et al. 1990; Scanlon et al. 2003). In these areas, increased recharge and salt mobilization related to conversion of natural ecosystems to rain-fed agriculture has resulted in numerous cases of groundwater salinization (Allison et al. 1990; Favreau et al. 2002; Scanlon et al. 2005). In addition, persistent groundwater abstraction in areas receiving little or no recharge often results in falling water tables, aquatic habitat degradation and other related consequences (Boulton et al. 2003).

In arid northwest China, intensifying agricultural and industrial activities are putting heightened strain on the region's limited water resources. Depletion of water resources in the Hexi Corridor region of Inner Mongolia and Gansu Province has become evident from several recent studies and includes diminished downstream flow in the Heihe River (Feng et al. 2004) and falling groundwater levels in the Minqin Basin and elsewhere (Edmunds et al. 2006). The Badain Jaran Desert has become central to discussions of water and agriculture in the region, not only as a major dust source to areas affected by desertification, but also because it contains shallow groundwater and a large number of groundwater-fed oasis lakes, which contrasts with the general trend of depletion in surrounding locations. As a result, the Badain Jaran has attracted substantial research interest in the water balance of the area and groundwater recharge in particular, and at least one suggestion that the desert groundwaters could be developed for agricultural and domestic use elsewhere in the region (Chen et al. 2004).

Proposed recharge sources to the Badain Jaran Desert have varied widely, and several authors have argued that direct recharge through the unsaturated zone may provide the primary source of water to the interdune lakes, which are groundwater-fed. Yang and Williams (2003) base this conclusion on major ion chemistry of lakes and shallow groundwater. Hofmann (1999) suggests the presence of two primarily separate groundwater flow systems, one fed by direct recharge and the other from a source external to the dune field. Jäkel (2002) proposes that the desert's complex dune morphologies may result in focused infiltration in many locations, with winter precipitation playing an important role in groundwater recharge. In contrast, Chen et al. (2004) argue that the desert's groundwater is derived from the Qilian Mountains (approximately 200 km to the southwest), transported through an extensive network of interconnected fractures, though little evidence is available to support this hypothesis. Most recently, a palaeowater origin for the shallow groundwater was proposed by Ma and Edmunds (2006) based on chemical and isotopic studies. They estimate current direct recharge through the unsaturated zone at approximately 1 mm/year.

Previous unsaturated zone studies in arid regions have shown that direct recharge is generally low and often subject to strong spatial variability (i.e. Sharma and Hughes 1985; Johnston 1987; Gieske et al. 1990; Edmunds et al. 2002; Dyck et al. 2005; Heilweil and Solomon 2004). For example, in the Murray Basin, South Australia, Allison et al. (1985) demonstrated that recharge rates for vegetated sand dunes are ~0.1 mm/year, but are three orders of magnitude higher in nearby sinkholes. Scanlon and Goldsmith (1997) report similarly high variability between playa and interplaya settings in the Texas Panhandle (USA) using chloride mass balance and tritium data. Edmunds and Gaye (1994) showed that recharge estimates from Cl in profiles drilled at the plot scale and those estimated from Cl concentrations at the water table in shallow groundwaters sampled through village wells over an area of 2,000 km^2 in Senegal were similar at 0.5–34 mm/year. A range of factors may influence recharge rates, including topography, land cover, vegetation, soil thickness and precipitation rate (Murphy et al. 1996; Petheram et al. 2002). Where variability in point recharge rates correlates with readily measurable environmental factors, these relationships can be used to calculate diffuse recharge fluxes or to map recharge. Such attempts have frequently involved GIS and remote sensing techniques (Brunner et al. 2004; Keese et al. 2005; Sophocleous 1992).

However, the focus of arid zone unsaturated zone research, including studies of spatial variability of recharge, has for the most part been restricted to areas with predominantly warm climate, and few cold desert unsaturated zone results are available in the literature. Research at the Hanford Site in Washington (160 mm/year precipitation; January mean temperature −1.5°C) has shown a range of recharge rates from near 0 to 3.4 mm/year, depending on soil type and land cover (Prych 1998),

 DOI 10.1007/s10040-007-0264-z

which is in line with results from many warm deserts (de Vries and Simmers 2002). Nevertheless, the net effects of persistent sub-zero temperatures on recharge patterns of cold deserts such as the Badain Jaran remain uncertain. For example, recharge could be precluded in winter months by layers of frozen near-surface soil moisture restricting infiltration (Zhao and Gray 1997), or in contrast, enhanced by focused recharge in topographic depressions which collect snow and ice blown in from surrounding dunes (Hayashi et al. 2003), which has been observed in the region (Jäkel 2004). Partial freezing of soils can also encourage bypass flow in the unsaturated zone due to pore-scale variability of ice formation and thawing (Lundin 1990; Stahli et al. 1996). Topographic setting is also considered a potential driver of variability in the Badain Jaran because of possible rain shadow or thermal effects of the large dunes. For example, after a rainfall event in July 2005, the southwestern flanks of the megadunes tended to dry faster than the northeastern, presumably due to more direct sunlight.

The primary objective of this study is to characterize spatial and temporal variability of direct recharge across the Badain Jaran dune field in northern China to assess whether recharge from desert precipitation is sufficient to support the area’s lakes, and what percentage of precipitation in this region contributes to shallow groundwater. The study also represents one of the first applications of unsaturated zone tracer methods to a cold desert environment.

Study area

The Badain Jaran desert lies near the centre of the Alashan plateau in western Inner Mongolia, between 39°20′N to 41°30′N and 100°E to 104°E (Fig. 1). It spans the region bounded by the Heishantou mountains (peak elevation 1,963 m asl) to the south, the Yabulai mountains (peak elevation 1,957 m asl) to the southeast, and the lowlands areas of the Gurinai grassland and the Guezi Hu wetlands (about 1,000 m asl) to the west and north (Hofmann 1996). With an area of approximately 49,000 km^2, it is the second largest desert in China (Yan et al. 2001).

The desert landscape primarily consists of sparsely vegetated aeolian sand dunes, including large “mega-dunes” up to 400 m high, which are strongly oriented in a

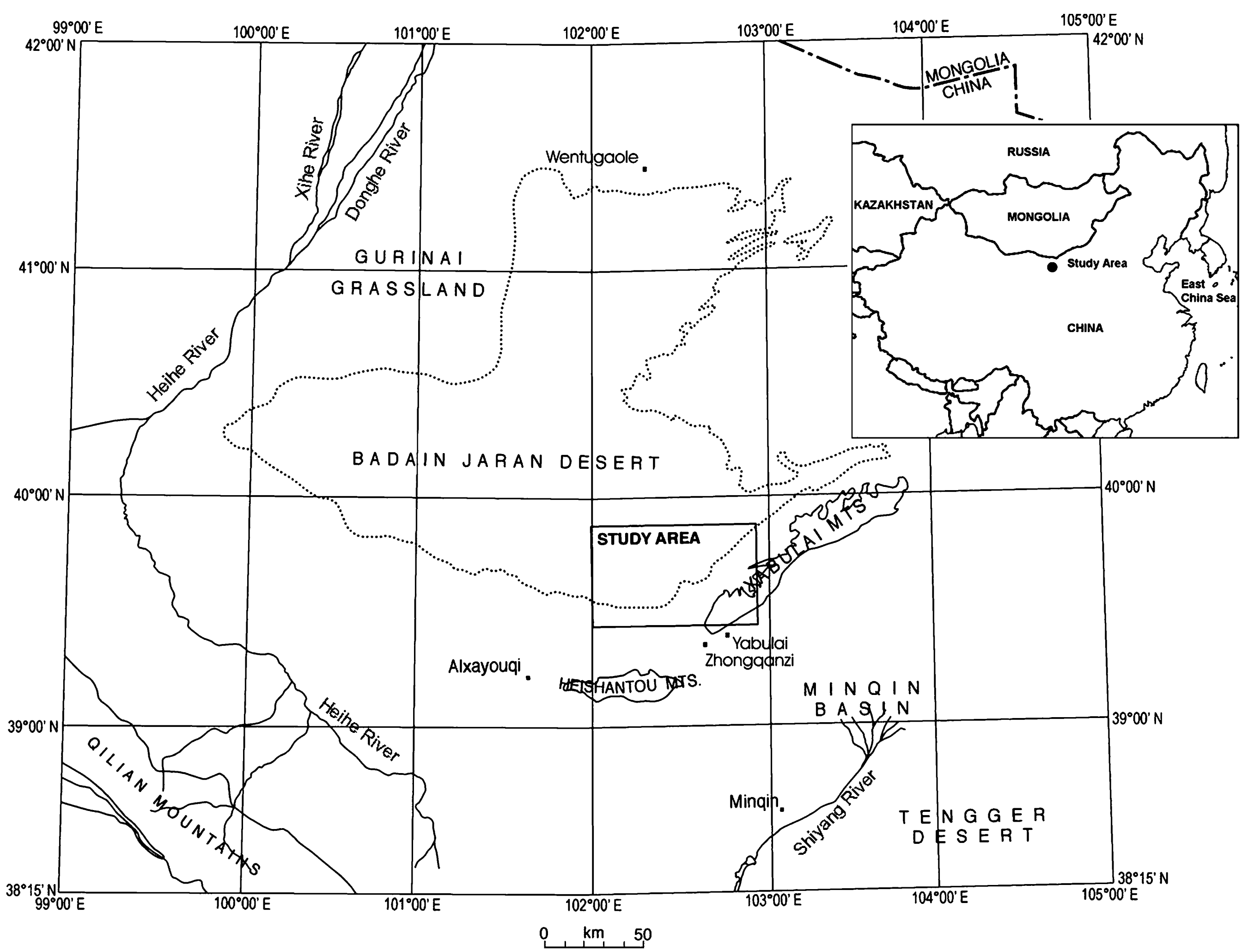

Fig. 1 Map of study area

 DOI 10.1007/s10040-007-0264-z

SW–NE pattern, and a range of smaller and more complex barchan and star-shaped formations (Dong et al. 2004). Many of the interdune areas contain groundwater-fed lakes, which vary widely in surface area (≤1.6 km^2) and salinity (1–398 g/L total dissolved solids, TDS) throughout the desert (Hofmann 1996; Yang and Williams 2003). Vegetation in the study area is variable with sparse xeric grasses and small shrubs (*Haloxylon ammodendron, Psammochoa villosa, Phragmites communis, Artemisia ordosica*), with denser groundcover observable as riparian strips around lakes and springs in many low-lying areas (*Polypogon monspeliensis, Triglochin maritima, Achnatherum splendens, Carex sp., Glaux maritima*).

The unsaturated zone in the study area consists mainly of moderately to well-sorted unconsolidated dune sands. The sands have a mean diameter of 0.22 mm, and follow a bimodal distribution characteristic of two significant source areas, most likely the Heihe River alluvial fan to the west and the Gobi Desert to the north (Jäkel 1996). Non-sand strata in the unsaturated zone encountered during sampling were limited to occasional layers of silt and organics near some lakes, which are likely remnants of lacustrine deposition during wetter periods, and one deposit of calcrete 7 m below a dune surface in the vicinity of Lake Baoritelegai. Unsaturated zone thicknesses range from over approximately 400 m on large dunes to very shallow (<1 m) in interdune areas.

Climatically, the Badain Jaran is strongly continental, with mean monthly temperatures from ~−10°C in January to ~25°C in July. Diurnal temperatures in summer months range from ~0 to >40°C. Precipitation is influenced by the Asian monsoon, with ~70% precipitation from July to September. Cold and dry continental air masses with temperatures below zero are dominant throughout the winter, though winter snowfalls occur occasionally (Jäkel 2002). The mean annual precipitation measured at Zhongqanzi Station (~20 km southeast of the study area) was 84 mm from 1956–1999 and is highly variable (SD 33 mm/year; Fig. 2), and potential evaporation is approximately 2,600 mm/year. Areas of frozen ground surfaces can be found locally between late October and early May (Jäkel 2004). Current climatic conditions reflect a relatively arid phase which began in the region approximately 4,000–6,000 years BP following a mid to late Holocene humid phase 10,000–6,000 years BP (An et al. 2006). Lake records from the region also provide evidence of intermittent, short-lived wet periods with rising lake levels over this period (Mischke et al. 2005; Zhang et al. 2004).

Few data are available regarding the hydrogeology of the region. The Holocene aeolian sands that make up the desert landscape have been deposited upon older Quaternary sediments that occupy the basin depression of the Alashan platform. The Quaternary sediments also comprise the desert's major shallow aquifer, which can be found at shallow depths in many locations and emerge as lakes in many interdune areas. Confined or semi-confined conditions are apparent in the vicinity of some lakes where travertine islands have formed as a result of fresh groundwater being forced upwards under pressure. Low-porosity lacustrine sediments or interbedded sandstone may provide the confining layers locally. Granitic basement rocks which outcrop along the Yabulai Mountains are found at a depth of approximately 80 m in the study area and may provide the lower confining unit for the shallow aquifer. Based on lake levels and water-table elevations in shallow domestic wells, the regional hydraulic gradient is from SE–NE, with the Gurinai Grassland

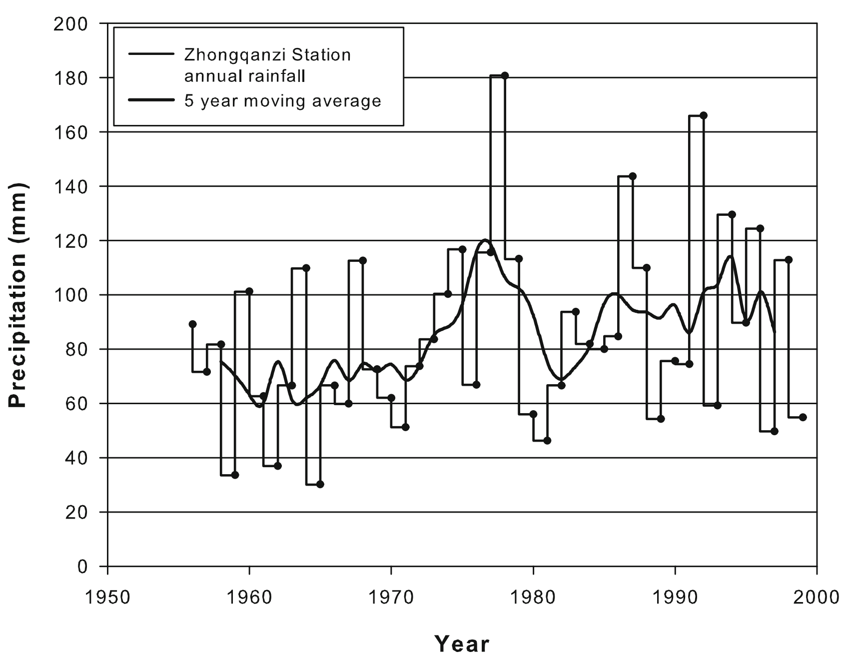

Fig. 2 Annual precipitation record for Zhongqanzi

DOI 10.1007/s10040-007-0264-z

area the probable location of discharge. Regional inputs to the shallow Quaternary aquifer and deeper groundwater systems are poorly understood.

Methodology

Profiles were collected during two field sessions in 2005 in the southeastern portion of the Badain Jaran where the highest density of lakes occurs (Fig. 3). Profile locations were chosen to characterize a range of environmental conditions present in the area which may affect recharge rates. The study sites were clustered into four groups around Sayin Wusu, Baddam, Baoritelegai and Noertu Lakes. In the field, samples were obtained using a hollow-stem hand auger (Dormer Engineering, Australia) with interchangeable 1.5-m aluminum rods from 18 profiles (6–16 m depth). Bulk sediment samples of approximately 500 g were collected at intervals ranging from 0.13 to 0.50 m. Samples were homogenized over the sampled interval and immediately sealed in polyethylene bags. Vegetation density at each coring site was estimated by a count of the number of individual plants within a 3-m radius of the drill site at the time of sample collection (mid-summer). Locations and elevations were recorded with Garmin GPS.

For chemical analyses, unsaturated zone moisture was extracted by elutriating 50 g of moist sediments with 30 ml of deionized water, then centrifuging and filtering supernatant at 0.45 μm. Cl concentrations of elutriated samples were analyzed using ion chromatography at the Oxford University Centre for the Environment and Bureau of Economic Geology, University of Texas, and soil moisture contents were determined gravimetrically after drying overnight at 110°C. Analytical precision was 3% of concentration based on reproducibility of samples and standards and the detection limit was approximately 0.1 mg/L.

Recharge rates were estimated using the chloride mass balance method, which balances the mass of Cl coming into the subsurface from precipitation with Cl output in potentially recharging water, and makes use of the fact that Cl in the unsaturated zone is inert (Allison and Hughes 1978):

$$P \times C_P = R \times C_R$$

where P is precipitation rate, C_P is Cl concentration in precipitation, R is recharge rate, and C_R is Cl concentration of potentially recharging pore waters (Edmunds et al. 1988). Cl in precipitation should be adjusted to account for dry deposition in aerosols. Recharge is inversely proportional to the degree of enrichment of Cl due to evapotranspiration.

Assuming piston-like vertical flow in the unsaturated zone, Cl can also be used to estimate the residence time of water at a given depth by dividing the total mass of Cl in

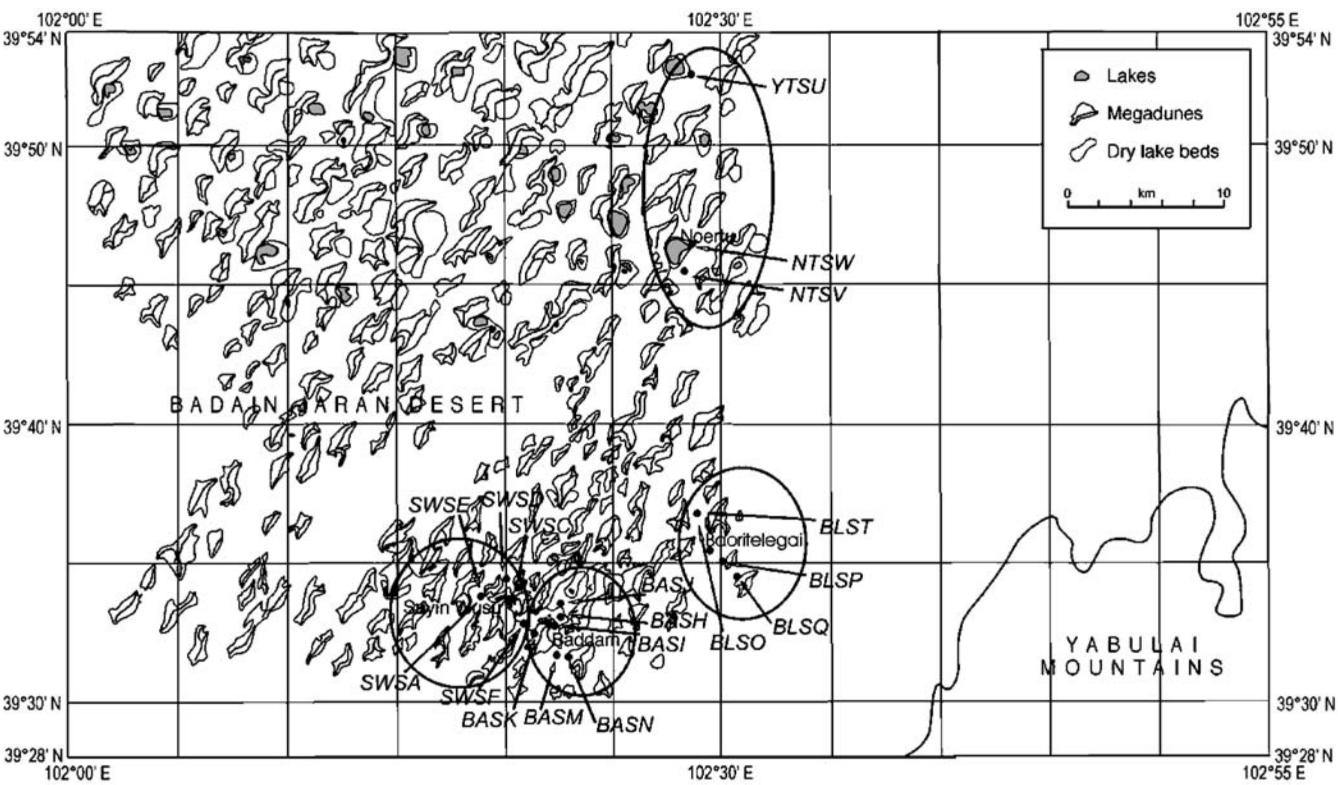

Fig. 3 Detail map of profile locations

DOI 10.1007/s10040-007-0264-z

the profile above a given depth by the annual Cl input rate:

$$t = \frac{1}{P \times C_p} \int_0^{z_i} \theta(z) C_r(z) dz,$$

where t represents residence time, θ is moisture content, and z is depth (Tyler et al. 1996). Standard statistical tools including Pearson's correlation coefficient and cross-correlation coefficients (for time series) are used for comparisons between the profiles.

Results and discussion

Soil moisture content

Visible soil moisture occurs from about 40 cm below surface in most locations in the study area, though it was encountered at depths as shallow as 23 cm in the case of BLSP05-10 (Fig. 4). Unsaturated zone soil-moisture

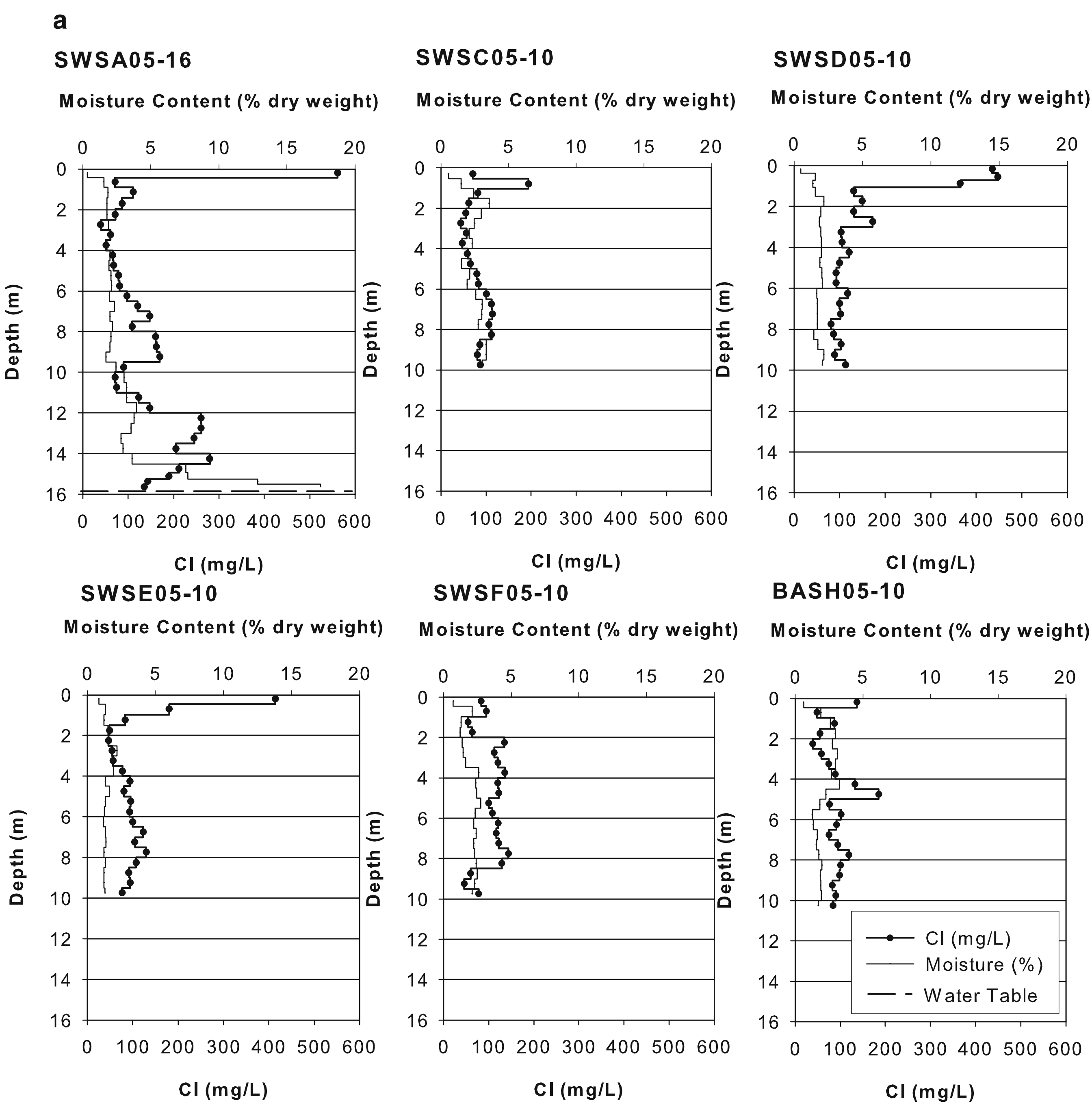

Fig. 4 Unsaturated zone profiles of Cl and moisture content

 DOI 10.1007/s10040-007-0264-z

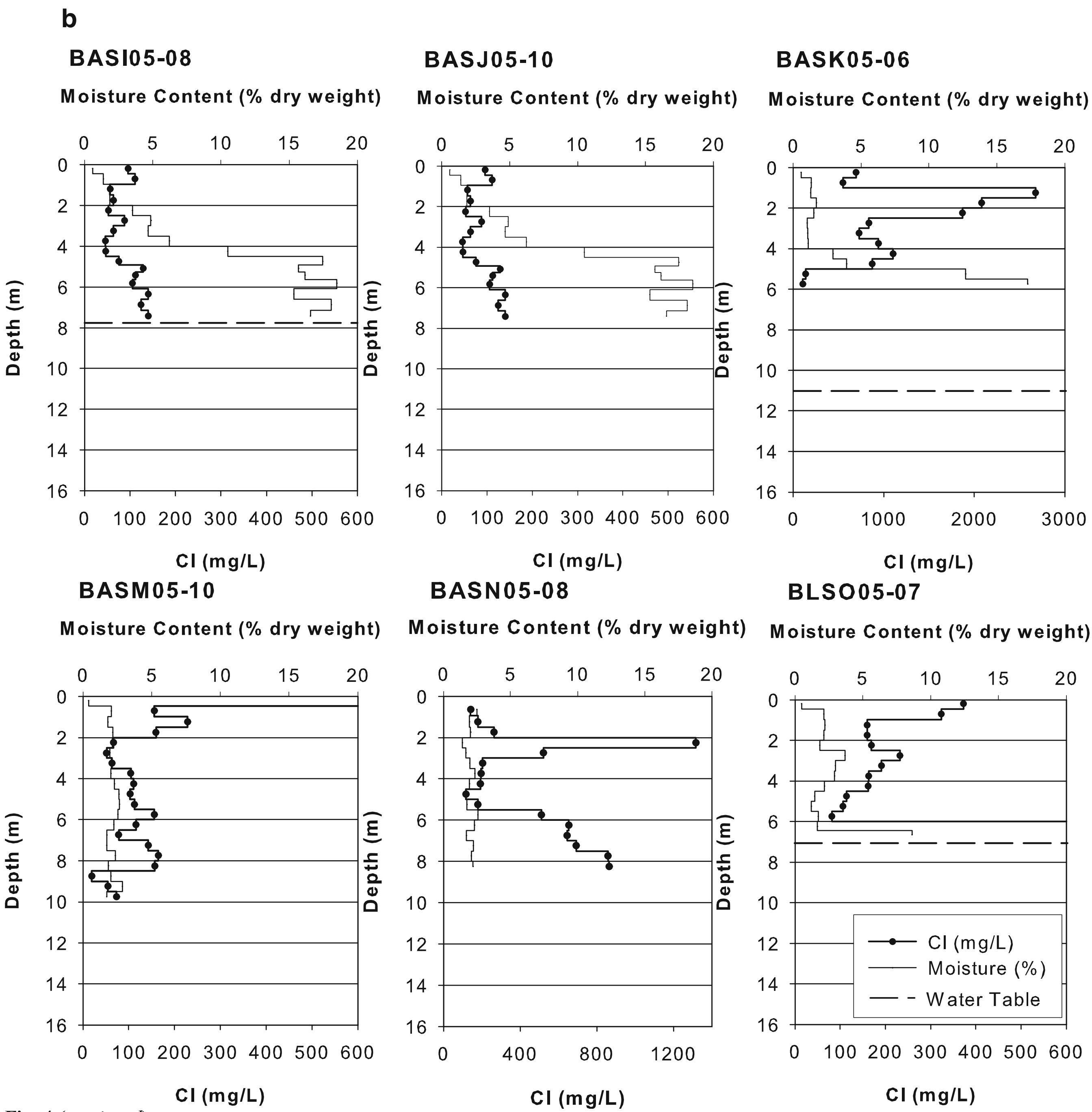

Fig. 4 (*continued*)

content is generally low (1–3%) and relatively constant with depth. Profiles BLST05-08, YTSU05-09 and NTSW05-10 were collected after rain events in July 2005, the effects of which are seen in elevated near-surface moisture contents (up to 5.8% at 0.7 m in the case BLST05-08). In BLST05-08, a wetting front had infiltrated to 0.5 m at the time of sampling due to a storm event two days prior, and is overlain by a dry layer. In YTSU05-09 and NTSW05-10, wetting fronts (from separate storm events of low intensity <12 h prior to sampling) are found at the surface and are restricted to the upper 0.1 m, below which are dry layers.

Four profiles (BLSO05-07, SWSA05-16, BASI05-08 and BASK05-06) show elevated moisture contents close to saturation (~21% of dry weight for sands) at the base of the profiles (at 7, 16, 8 and 6 m depth, respectively) that are attributed to capillary effects from the underlying water table. This is supported by comparison of profile base elevations with the position of the regional water table as estimated by nearby lakes (see Table 1). Water-

 DOI 10.1007/s10040-007-0264-z

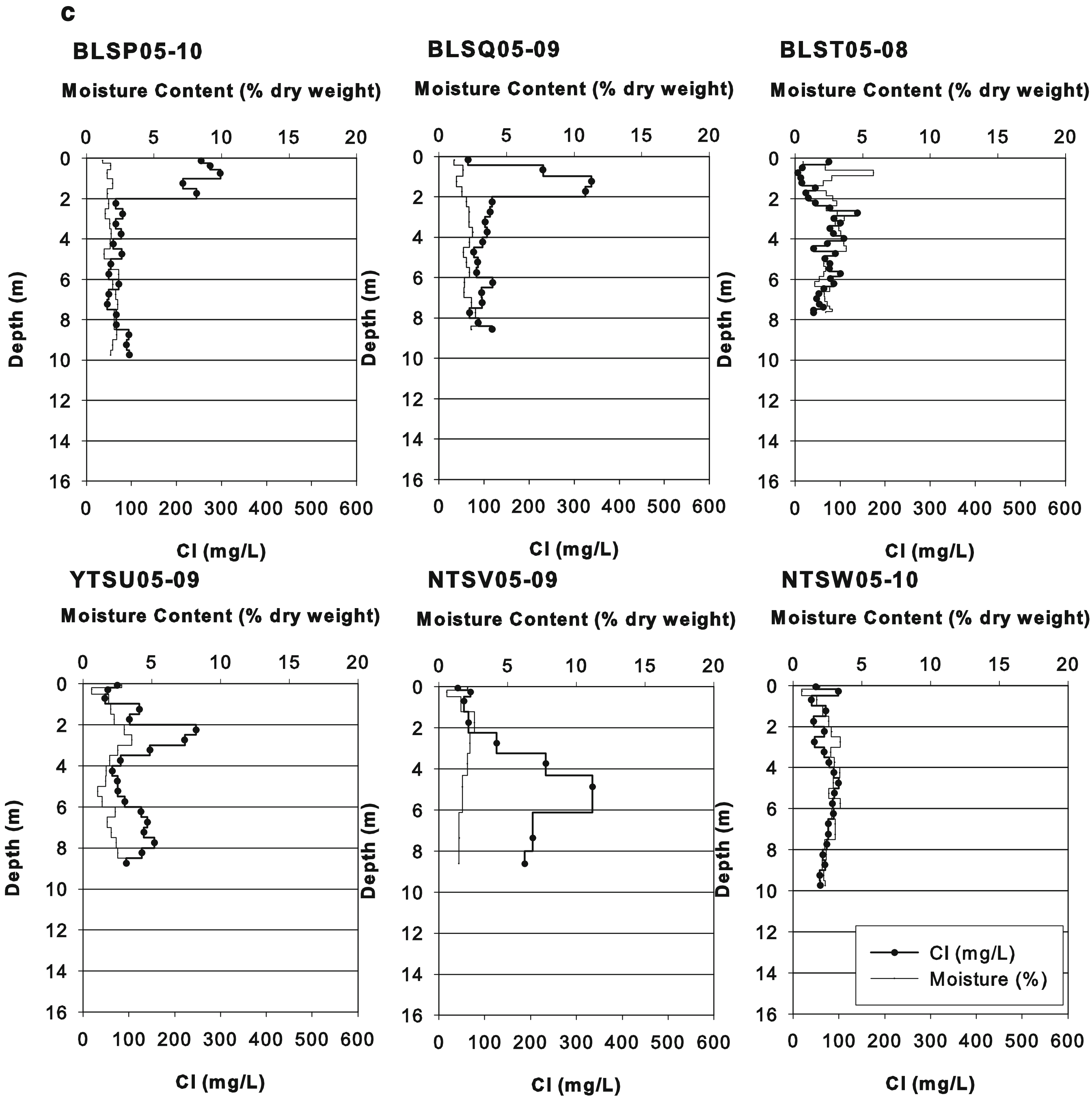

Fig. 4 (*continued*)

table effects on capillary Cl concentrations appear highly variable, which may partially reflect the large range of groundwater concentrations found in the area (Table 4). In the case of BLSO05-07, Cl concentrations are one order of magnitude higher in the capillary samples than the rest of the profile (5,795 mg/L at 6 m depth and 1,066 mg/L at 6.5 m depth); a remnant of palaeolake salts is likely the source for the high-salinity shallow groundwater (the profile is located about 600 m from Lake Baoritelegai).

Vertical distribution of Cl

Most profiles exhibit near-surface peaks in Cl, generally from 0.75 to 2.25 m, which generally represent maximum values for each profile, with the exception of SWSF05-10, BLST05-10 and NTSW05-10) which have no obvious peak (Fig. 4). In the case of YTSY05-09, the peak appears unusually deep at 2.25 m. In BASH05-10 and BASJ05-10, near-surface concentrations are surpassed by concentrations in one or more peaks at lower

DOI 10.1007/s10040-007-0264-z

Table 1 Summary of profile characteristics

Profile ID	Average Cl (mg/L)	Near-surface Cl peak (mg/m^2)	Recharge (mm/year)	Avgerage moisture (% dry wt)	Vegetation density ($plants/m^2$)	Local dune slope (Degrees)	Orientation to megadunes	Elevation (m asl)	Basin	Depth (m)	To water table (m)
SWSA05-16	120	5,148	1.12	2.4	0.71	Depression	SW	1,219	Sayin Wusu	16	0
SWSC05-10	80	5,190	1.68	2.8	0.32	0	SE	1,225	Sayin Wusu	10	10
SWSD05-10	111	7,590	1.2	1.9	0.07	4	SE	1,260	Sayin Wusu	10	50
SWSE05-10	87	2,189	1.54	1.5	0.21	6	NW	1,223	Sayin Wusu	10	10
SWSF05-10	103	N/A	1.29	2.2	0.04	Depression	NE	1,233	Sayin Wusu	10	20
BASH05-10	89	699	1.50	2.2	0.53	4	SW	1,222	Baddam	10	10
BASI05-08	76	1,954	1.76	2.8	0.00	0	N/A	1,209	Baddam	8	0
BASJ05-10	164	9,930	0.82	2.8	0.99	5	SW	1,222	Baddam	10	10
BASK05-06	N/A	N/A	N/A	1.9	1.10	0	NW	1,201	Baddam	6	5
BASM05-10	111	5,838	1.20	2.2	0.21	9	NE	1,287	Baddam	10	80
BASN05-09	N/A	27,753	N/A	2.1	0.00	24	NW	1,282	Baddam	9	70
BLSO05-07	N/A	8,105	N/A	2.3	0.28	3	NW	1,297	Baoritelegai	7	0
BLSP05-10	69	11,306	1.92	1.9	0.07	8	NW	1,320	Baoritelegai	10	35
BLSQ05-09	97	12,729	1.37	2.3	0.18	0	SE	1,320	Baoritelegai	9	35
BLST05-10	62	N/A	2.16	2.8	0.04	8	NW	1,323	Baoritelegai	8	40
YTSU05-09	109	N/A	1.23	2.0	0.11	0	S	1,208	Yindertu	9	25
NTSV05-10	N/A	N/A	N/A	1.8	0.39	10	NW	1,221	Nouertu	9	40
NTSW05-10	71	N/A	1.88	2.6	0.00	0	S	1,215	Yindertu	10	25

Depth refers to the profile length rounded to nearest m. "To water table" refers to vertical distance from profile base to estimated water table depth based on nearby lake levels (rounded to nearest 5 m)

depths. Near-surface Cl peaks range from approximately 100 to 1,300 mg/L, and account for between 699 and 27,753 mg/m^2 of accumulated Cl (Table 1). Below the near-surface peaks (and above capillary effects in some cases), Cl concentrations fluctuate generally within a range of 50–200 mg/L.

Notable exceptions to this general pattern are BASN05-08, BASK05-06, NTSV05-10 and BLSO05-07, which do not approach consistent mean values over the sampled depths. Some of these discrepancies could be explained by the occurrence of bypass flow, which is suggested by elevated Cl concentrations at depth. Although no heterogeneities in the profile stratigraphies suggest this, partial freezing in these locations could result in near-surface preferential flow. Horizontal components of unsaturated flow can also occur in sloping terrain even without strong heterogeneity in unsaturated zone materials (McCord and Stephens 1987). In the case of BASJ05-10, an unusually high density of vegetation at the profile site may have had an impact (see the following).

The presence of Cl peaks in (semi-) arid unsaturated zone profiles is widespread and has been shown in numerous locations globally (Phillips 1994; Scanlon 1991; Stone 1992). Solutes tend to accumulate in the near-surface where evaporation and transpiration processes are actively removing moisture which has been deposited by precipitation. Though diffusion also plays a role, the Cl which has been concentrated by evapotranspiration generally remains in this mixing zone until it is flushed downward by infiltrating water. In the southwestern US, large near-surface bulges of Cl have been interpreted as accumulations since the onset of the Holocene, with no recharge occurring since that time. Badain Jaran profiles exhibit much lower levels of accumulation despite average rainfall of less than 100 mm/year and potential evaporation of 2,600 m/year. Taking input values described above, observed peaks correspond to Cl accumulation times of between 20 and 200 years. Assuming bypass flow is insignificant, these accumulation times can serve as approximate indicators of the length of time since the last significant infiltration event. The relatively low amounts of subsurface Cl accumulation suggest that occasional recharge events occur in the study area under modern climatic conditions. These are likely associated with intense summer storm events.

Spatial variability

For the purposes of assessing spatial variability and calculating recharge rates, the average Cl concentration for each profile was calculated as the arithmetic mean of depth-weighted Cl below the near-surface peak, which is associated with the active mixing zone where solutes and water are recycled as a result of evapotranspiration fluxes. Samples from the capillary fringe were also excluded because they may include solutes not derived from unsaturated flow. Mean values for each profile range from 62 to 164 mg/L (mean 96 mg/L), excluding BASN05-08,

DOI 10.1007/s10040-007-0264-z

BASK05-06, NTSV05-10 and BLSO05-07 (Table 1; Fig. 5). Confidence intervals have been calculated for each of the means which take into account (1) standard deviations of mean Cl in the profiles (for α=0.05) and (2) analytical error of 3%. There is much overlap in the Cl concentrations at the 95% confidence level, and the highest profile average (BASJ05-10) is within a factor of three of the lowest (BLST05-08).

Profile means for Cl are not related to geographical location within the study area (Figs. 3, 6 and 7). For example, the Baddam group includes the profile with the highest concentration as well as the fourth lowest and one near the median. Moreover, variances within geographic groupings are similar to the overall variance, and no significant difference exists between the highest (110 mg/L for Baddam) and lowest (76 mg/L for Baoritelegai) group averages (p=0.23 for two-tailed t-test).

To ensure an unbiased estimate of diffuse recharge, it is important to identify any environmental factors which may affect recharge rates. However, Cl profiles are not related to position relative to major dune formations (Fig. 7). Profile sites in closed topographic depressions had slightly higher Cl concentrations, indicating that recharge may even be slightly lower than average in these locations relative to uniform slopes and flat surfaces. Mean Cl concentrations and vegetation density within a 3 m radius of the boreholes are weakly correlated at plant densities = 0.2 plants per m^2 (r=0.63; Fig. 8). The profile location with the highest vegetation density (BASJ05-10) also has the highest Cl concentration. The number of individual plants within 3 m of profiles ranged from 0 to 28 (or 0–1 plants/m^2), though areas with 1 plant/m^2 are uncommon in the study area apart from immediately adjacent to lakes. The correlation between Cl concentration and vegetation density indicates that transpiration has a greater impact on potential recharge as vegetation density increases. However, this interpretation is heavily reliant upon the small number of observations at higher densities, and additional data would be desirable to better characterize the relationship.

The relatively low variability of recharge rates can largely be attributed to homogeneity in land cover and unsaturated zone materials (as well as insignificance of runoff). However, in order to further refine estimates of diffuse recharge in the Badain Jaran, a better understanding of the role of variable vegetation in controlling deep drainage will be required. The relationship between xeric vegetation and recharge suggested by these results is in line with findings from numerous previous studies, emphasizing the strong impact of transpiration on soil water potentials and deep drainage, as well as the impacts of land clearance, establishment of intensive agriculture, and other perturbations on the water balance (Walvoord and Phillips 2004). The simple proxy measurement of vegetation density used in this study does not take into account other relevant factors such as variable species composition and rooting depth, which may also affect recharge rates.

Chloride inputs

In order to convert unsaturated zone Cl concentrations into recharge rates, Cl deposition must be specified. In addition, the derivation of a diffuse recharge estimate for the Badain Jaran based on the results above requires a full accounting of uncertainty in mass balance inputs and spatial variability of Cl contents. Precipitation monitoring records from the multiple stations surrounding the Badain Jaran Desert show annual average rainfall values on the order of 100 mm/year. Precipitation 100 km southeast of the study area in Minqin averages 116 mm/year. Nearby monitoring stations in Youqi and Yabulai report averages of 114 and 80 mm/year, respectively (Domros and Peng 1988). To the north of the Badain Jaran and transitioning into the Gobi Desert, average precipitation decreases significantly to 50 mm/year at Wentugaole near the border between China and Mongolia (Domros and Peng 1988). For recharge calculations, a mean annual precipitation of 84 mm/year was adopted from the nearest monitoring station to the study area (Zhongqanzi, approximately

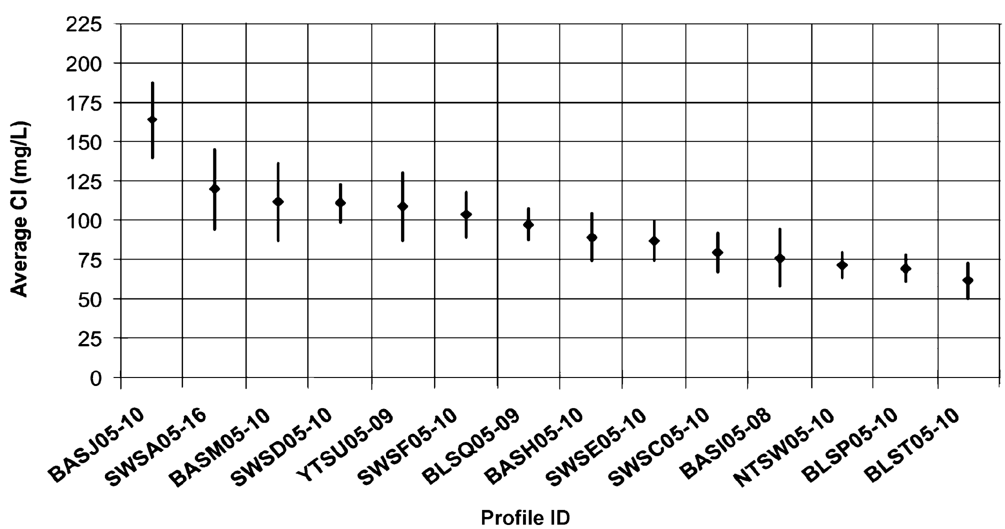

Fig. 5 Average Cl concentrations by profile with 95% confidence intervals

 DOI 10.1007/s10040-007-0264-z

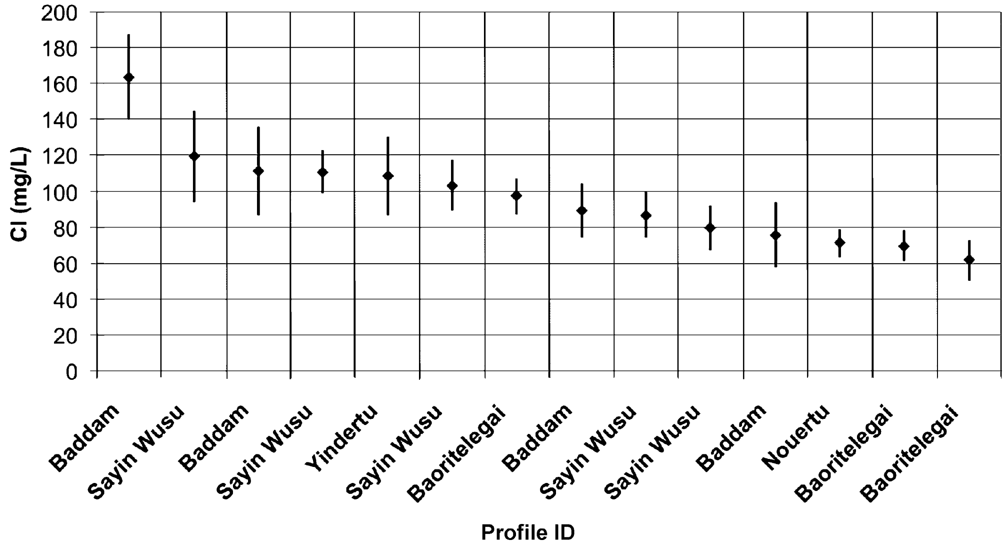

Fig. 6 Average Cl concentrations by basin group with 95% confidence intervals

20 km southeast of the study area). The rainfall record at Zhongqanzi Station spans the period 1956 to 1999 and has a standard deviation of 33 mm/year, with the wettest year on record (181 mm in 1978) six times the lowest (30 mm in 1965), reflecting the high temporal variability of precipitation in the study area (Fig. 2). To account for this, the 95% confidence interval around the mean is also considered in the recharge calculations (74–94 mm/year).

Records of solute concentrations in rainfall are sparse in most areas and are unavailable for much of China. Even where extensive records are available, this can be a difficult parameter to estimate because of high spatial and temporal variability. For example (Goni et al. 2001), found that solute concentrations tended to decrease over the course of the rainy season in the Sahel region of Africa, tentatively attributed to decreasing importance of localized dust sources over time. Ma and Edmunds (2006) base their estimate of Cl content in Badain Jaran rainfall of 1.5 mg/L on the weighted mean of precipitation from 2001–2002 in Zhonqanzi and one large storm in 1999 (approximately 50 mm), which represented the majority of precipitation for the calendar year. They also report 36.5 mg/L Cl in a small rain event in the same year, the magnitude of which may be indicative of local aerosol recycling, and which has a negligible effect on the annual weighted mean. Hofmann (1999) reported solute concentrations from ten storm events in the Badain Jaran in 1994 and 1995, with Cl concentrations from 0.5 to 19.1 mg/L. Six of these events fall within the relatively constrained range of 0.5 to 3.3 mg/L Cl with a simple (i.e. not volume-weighted) mean of 1.9 mg/L, though no rainfall amount data are available to confirm whether these measurements represented the majority of the year's rainfall. Volume weighted average Cl concentration in rainfall was 1.7 mg/L from 2000–2005 for three rural monitoring stations in the vicinity of Xi'an (34°14′N; 108°57′E), 750 km southeast of the study area, the closest monitoring station with multiple years of data available (EANET 2006).

The value of 1.5 mg/L measured by Ma and Edmunds (2006) was adopted as the best available estimate for Cl

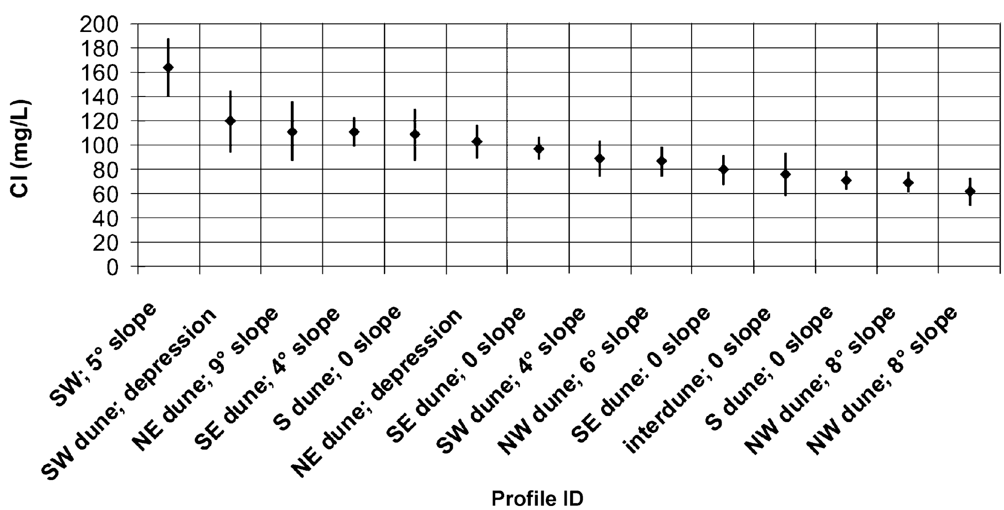

Fig. 7 Average Cl concentrations by topographic orientation with 95% confidence intervals

 DOI 10.1007/s10040-007-0264-z

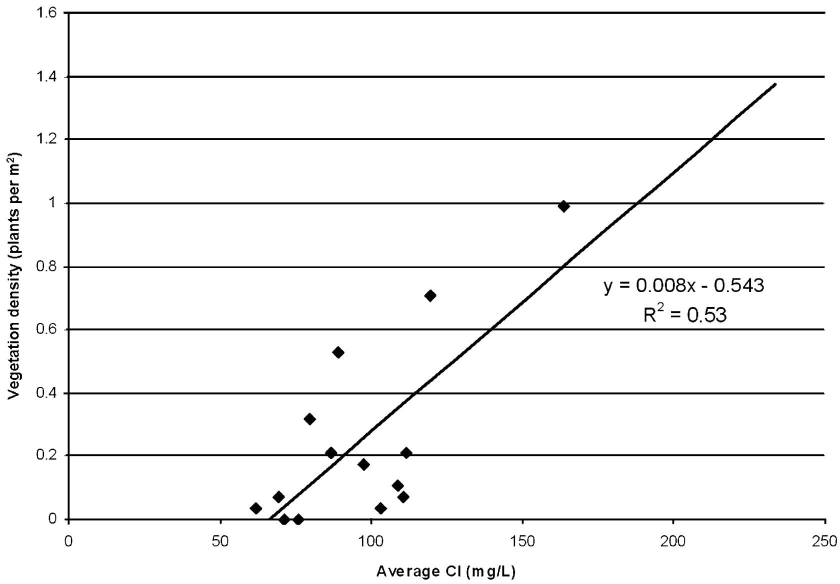

Fig. 8 Scatter plot of average Cl vs. vegetation density

concentration in rainfall in the study area. However, no data are available regarding the annual contribution of dry deposition of Cl in the region. Bulk rainfall samples tend to include inputs from dry deposition with rain samples, but provide no record of deposition during extended dry periods, the net bias of which is difficult to estimate. If the long-term aerosol flux in the region is near steady state, then the average net flux of dry season aerosol deposition should be negligible (Goni et al. 2001), in which case the bulk wet season samples would accurately reflect overall inputs, but would tend to underestimate inputs if not. A current steady state balance of Cl aerosol fluxes is considered doubtful in this region considering the increasing erosion rates as well as widespread cases of soil salinization across northwestern China. As such, 1.5 mg/L is taken as a lower bound for the purpose of recharge calculations. Using a liberal estimate of 50% of total Cl deposition occurring as dry deposition during the dry season (Dettinger 1989; Selaolo et al. 1994), total Cl input flux is likely to fall within the range of 126–252 mg m^{-2}/year (equivalent to 1.5–3.0 mg Cl L^{-1} for 84 mm/year precipitation).

Temporal variability in drainage

Below the near-surface mixing zone, if piston flow is dominant and the direction of pore-water movement is vertically downward, then pore waters found at lower depths will have ages (i.e. times elapsed since infiltration) greater than those at shallower depths. In this case, fluctuations in Cl along the length of the profile will correspond to variations in recharge (proportional to 1/Cl) over time (Cook et al. 1992), with higher values for 1/Cl indicating lower recharge. Figure 9 shows 1/Cl plotted in time for each profile using the Cl-based chronology established with Eq. 2. Total accumulation times for these profiles average approximately 200 years. The length of time represented by individual samples varies based on vertical sampling density and Cl concentrations. For example, in YTSU05-09, temporal resolution varies between 4 and 21 years per sample for a sampling interval of 0.5 m. Also, solute accumulation times differ between profiles due to varying profile depths, Cl concentrations and moisture contents, which may be a consideration when comparing profile characteristics.

Several general features are common to a majority of the recharge histories. For example, comparison of profiles SWSA05-16 and SWSC05-10 shows that both have their oldest recorded peak of 1/Cl prior to 1800, a smaller peak around 1850 (slightly before in the case of SWSC05-10 and slightly after in SWSA05-16), and a gradual increase to a large peak in 1950 followed by a decrease through the 1990s. The 1950 peak in both cases is interrupted by a slight dip. While these two have the greatest similarity (r=0.81), many profiles have some prominent features in common with them and each other. In total, 9 of 13 of the profiles analyzed (see the following) are consistent with this general pattern, though a large degree of variation in peak magnitudes, and to a lesser degree the chronology, is portrayed. The prominent peak between 1750 and 1800 is shared by SWSA05-16, SWSC05-10, SWSF05-10, BASM05-10, BLSO05-07, BLSQ05-09, YTSU05-09 and NTSW05-10, and a maximum in 1/Cl in between 1950, and the present is shown in all of the records which include that period of time (note that some records do not extend to the present because of the time period which is represented by near-surface Cl accumulations).

Four profiles (BASN05-08, BASK05-06, NTSV05-10 and BLSO05-07) have been excluded from this analysis because they do not appear to reach consistent mean values over the length of the profile. In the case of BLSO05-07, it may be because the capillary zone begins at only 6.5 m depth, leaving only 5 m between the near-

 DOI 10.1007/s10040-007-0264-z

Table 2 Cross-correlation coefficients (*top right*) and number of years for comparison (*bottom left*)

	SA	SC	SD	SE	SF	SH	SJ	SM	SP	SQ	ST	SW	SU
SWSA05-16		0.81	0.06	0.49	0.16	0.75	0.35	0.10	0.21	0.41	−0.01	0.33	0.07
SWSC05-10	201		−0.22	0.38	−0.09	0.65	0.75	0.52	−0.18	0.34	−0.45	0.15	−0.09
SWSD05-10	180	164		0.53	0.20	0.20	0.43	0.09	−0.01	0.61	0.36	0.58	0.53
SWSE05-10	111	99	62		−0.15	0.52	0.89	0.26	0.41	0.62	−0.43	0.83	0.76
SWSF05-10	230	201	164	111		0.14	0.51	−0.28	0.46	0.63	0.19	0.22	0.04
BASH05-10	212	188	151	111	212		0.72	0.06	−0.11	0.44	−0.23	0.57	0.44
BASJ05-10	171	125	141	23	125	112		0.31	−0.17	0.47	0.78	0.63	0.077
BASM05-10	188	169	180	67	169	156	144		−0.10	−0.27	−0.18	−0.33	−0.19
BLSP05-10	114	114	114	54	114	114	83	114		−0.06	0.32	−0.4`	0.07
BLSQ05-09	154	145	154	43	145	132	134	154	103		0.43	0.34	0.49
BLST05-10	139	102	65	111	131	126	26	70	57	46		0.128	0.477
NTSW05-10	209	171	134	111	200	195	95	139	114	115	139		0.561
YTSU05-09	277	201	180	111	230	212	162	188	114	154	139	209	

surface peak and the capillary zone. The BASN05-08 profile was located on the flank of a large dune on a slope of 23°. It is probable that rapidly shifting sands may have affected the site, altering the solute profile.

The overall degree of agreement in the recharge histories can be characterized using time series cross-correlations. The cross-correlation calculations require time series data at regular (i.e. constant) intervals. For this purpose, series with 1-year intervals were constructed from 1/Cl values with a cubic spline interpolation (linear boundary condition). The resulting correlation coefficients (r) are shown in Table 2. The greatest agreement between any two time series is between SWSA05-16 and SWSC05-10 with r=0.81, though several other strong correlations were found. Correlation coefficients are heavily skewed toward the positive side, indicative of the general agreement of the profiles (Fig. 10). The bimodal nature of the distribution (centered on r=0.1 and r=0.5) suggests that a subset of the records are in general agreement with one another, and another subset of approximately equal size that has little or no mutual correspondence. This distribution becomes further skewed toward the positive if time lags between the records are allowed. For example, the strongest anticorrelation (r= −0.45 between BLST05-10 and SWSC05-10) becomes 0.3 with a time lag of 83 years. It is uncertain whether the apparent time lag is actual or due to a discrepancy in the Cl-based chronology, possibly from a local difference in Cl input. It is also unclear why some profiles (BASJ05-10, BLSP05-10, SWSD05-10) do not reflect this common pattern.

The similarities in recharge history of a number of the profiles are notable and support the assumption of piston flow in those profiles. While several limitations apply, including possible mixing in the unsaturated zone (Cook et al. 1992), uncertain Cl inputs, and only partial consistency in signals across the profiles, a relationship may exist between Cl concentrations and recharge which may be attributable to climate fluctuations in the study area in the past ~200 years. Although the value of this data set for the purpose of reconstructing recharge history is limited, it is important to consider these temporal variations when assessing spatial variability because profile lengths over which the averages were calculated represent different time periods. For example, the average Cl content for SWSF05-10 (103 mg/L) which contains the peak in 1/Cl at about 1750 would be slightly higher if only the top 8 m is considered (111 mg/L). Therefore, the comparison between SWSF05-10 and SWSE05-10, for example, is somewhat biased because one extends to 1850 and the other only to 1750. A full accounting of the effect of this bias on spatial variability is not possible because only 30 years of record are common to all of the profiles. However, the example of SWSE05-10 and SWSF05-10 illustrates that the means do not generally become more uniform when comparing only the period of record common to both profiles (in this case 87 and 119 mg/L, respectively, over the period 1870–1980).

Calculation of recharge rates

The total Cl accumulation times for the profiles of 200–300 years place their chronologies well within the onset of the modern arid climatic phase in the study area. As such, although temporal variability in recharge is apparent, long-term average recharge rates portrayed in the profiles are indicative of modern recharge conditions. The spatial variability results for mean Cl in each profile do not allow for refinement of the diffuse recharge estimate because no strong correlations with environmental factors could be established. Nonetheless, the overall variability is quite low, with a range of 0.82 to 2.16 mg/L. Vegetation density is taken into account for the diffuse recharge estimate because it has an effect on recharge at higher density sites. Figure 8 suggests that the positive relationship between vegetation density and mean Cl begins to emerge where approximately ten plants are present within a 3 m radius (~0.35 plants per m^2). Apart from immediate near-shore areas around lakes, such “high” vegetation densities are rare in the study area and were difficult to locate during field investigations. Although no comprehensive land cover data are available, field reconnaissance suggests that such areas form an insignificant fraction of total surface area.

 DOI 10.1007/s10040-007-0264-z

Because of the uncertainty introduced by imprecise input values (long-term average rainfall amount and Cl concentration in rainfall) and spatial variability, it may be most appropriate to report estimates of diffuse recharge as a range rather than a single value. For chloride mass balance calculations, four cases are considered for average Cl in unsaturated-zone pore water. In decreasing magnitude these are: (1) the upper 95% confidence level for mean Cl calculated including sites of high vegetation density, (2) mean Cl calculated including sites of high vegetation density, (3) mean Cl calculated excluding sites of high vegetation density (>0.2 plants per m^2) and (4) the

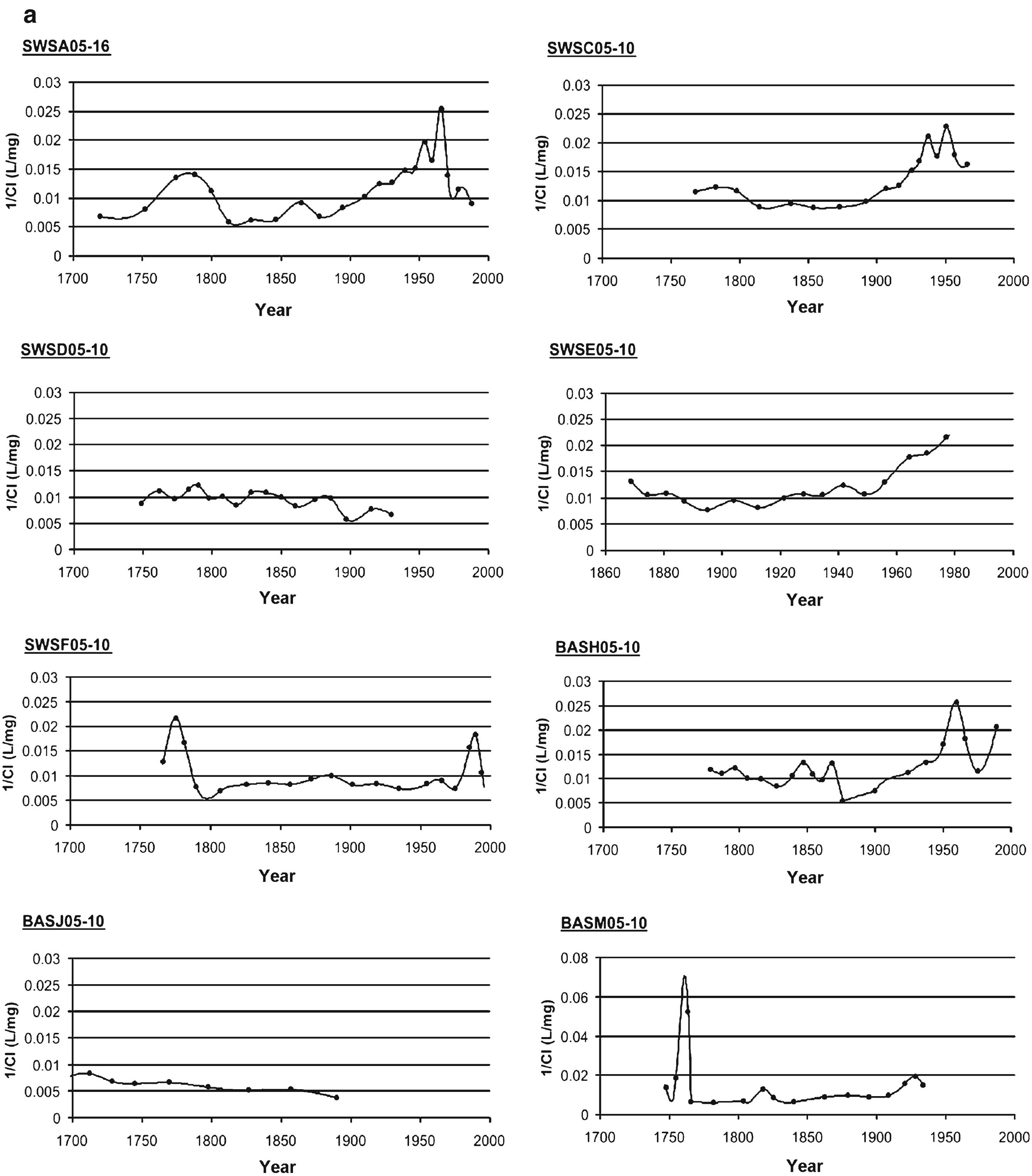

Fig. 9 Time-series plots of 1/Cl

DOI 10.1007/s10040-007-0264-z

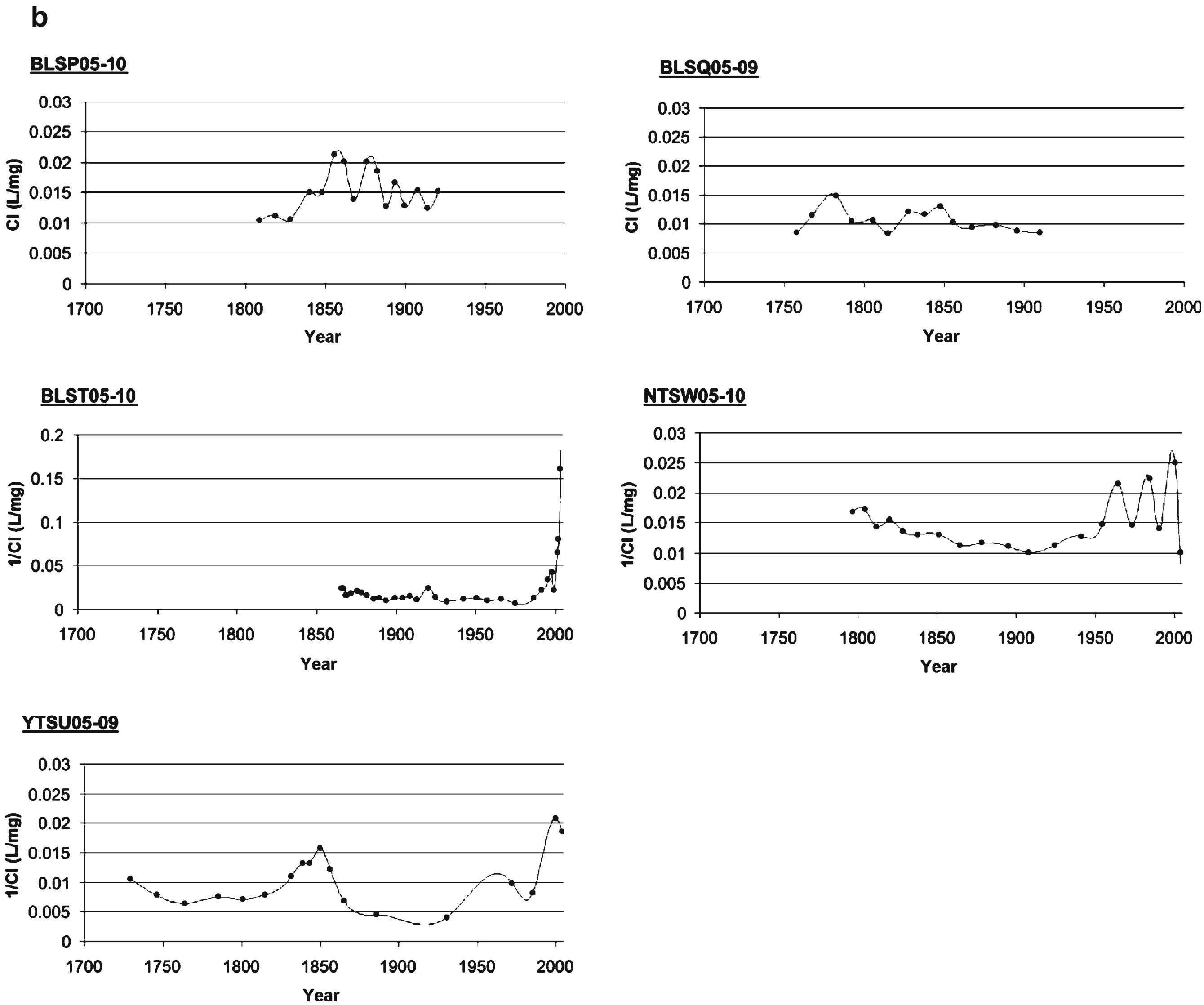

Fig. 9 (*continued*)

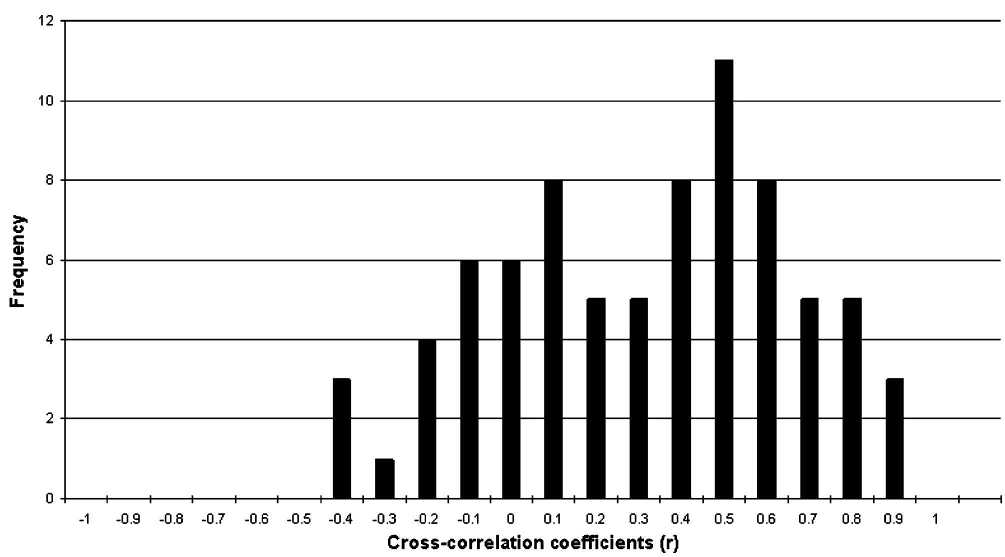

Fig. 10 Histogram of pair-wise cross-correlation coefficients for 1/Cl time series

DOI 10.1007/s10040-007-0264-z

Table 3 Recharge rate sensitivity matrix

P	95% Upper bound	95% Upper bound	95% Lower bound	95% Lower bound	Average
C_p + dry deposition	Low	Low	High	Low	Expected
C_r estimate 1 (mg/L)	2.6	2.0	1.3	1.0	1.1
C_r estimate 2 (mg/L)	2.9	2.3	1.5	1.2	1.3
C_r estimate 3 (mg/L)	3.2	2.5	1.6	1.3	1.4
C_r estimate 4 (mg/L)	3.6	2.8	1.8	1.4	1.6

"Expected" C_p + dry deposition equivalent to 1.5 mg/L, representing the case that long-term net dry-season aerosol deposition is zero

lower 95% confidence level for mean Cl calculated excluding sites of high vegetation density.

A matrix illustrating the outcomes of these scenarios is shown in Table 3. In general the uncertainty in input values is responsible for more variance than the mean Cl scenarios for pore waters, because both are linearly related to recharge in Eq. 1 and potential Cl inputs span a larger range of values. The maximum calculated recharge rate is 3.6 mm/year for the unlikely scenario of 94 mm/year rainfall (the upper bound at the 95% confidence level), the equivalent of 3 mg/L Cl in rainfall including dry deposition, and 77.9 mg/L Cl in the unsaturated zone (the lower bound at the 95% confidence level for the mean calculated without high vegetation density sites). The minimum calculated value was 1.0 mg/L for similarly extreme input values. The most likely diffuse average recharge value is taken to be 1.4 mm/year for the scenario including 84 mm/year precipitation, 1.5 mg/L Cl in precipitation, zero net dry deposition in the dry season, and 88.7 mg/L Cl in pore waters (the mean value of profiles with low vegetation densities).

Importance of diffuse recharge in the Badain Jaran

The estimated 1.0–3.6 mm/year of recharge represents approximately 1–2% of annual precipitation, which is consistent with results from warmer arid regions. The minor contribution of direct recharge to the shallow aquifer is illustrated by comparison with evaporation losses from the lakes. For the total potential catchment area of 2,500 km^2 for the study area's lakes (locations within the dune field to the east and south, based on head gradients), the total diffuse recharge flux is approximately 3.75×10^6 m^3/year. This is one order of magnitude lower than estimated evaporation losses from the combined lake surface area of 16.94 km^2 (Hofmann 1999) with 2,600 mm/year of evaporation (4.4×10^7 m^3/year). Diffuse recharge would have to reach at least 17.6 mm/year, or approximately 20% of annual precipitation, to offset losses from the lakes. This implies that other sources of recharge are of much greater importance to the shallow aquifer.

A chemical discontinuity exists between the unsaturated zone and the capillary zone in two of the three profiles that portray capillary effects on moisture contents. A wider comparison between Cl concentrations in the unsaturated zone with those in groundwater can be made using published data from wells and springs in the area (Table 4). Cl concentrations in groundwater appear highly variable, ranging from 63 mg/L at Lake Noertu to a maximum of 383 mg/L at Baddam. A large range is also apparent within the vicinities of Baddam and Baoritelegai. While many of the values in Table 4 are within the range of mean Cl concentrations of the unsaturated zone profiles, the higher salinity groundwater in the Baoritelegai and Baddam areas lie well outside of this range. However, because it is possible that the chemistries of some groundwater sample locations have been altered by reflux of high-salinity lake water, a chemical correspondence between the unsaturated zone and groundwater cannot be rejected solely on this basis. Nonetheless, groundwater primarily fed by diffuse recharge would be expected to portray more uniformity in solute concentrations since no strong spatial trend in recharge rates is present.

Conclusions

Direct recharge in the Badain Jaran Desert was estimated from mean Cl in 18 unsaturated zone profiles with depths from 6 to 16 m using the chloride mass balance method. Variability was generally quite low, with mean Cl contents among profiles within a factor of three. The low variability contrasts with results from some other arid regions (Allison et al. 1985; Heilweil and Solomon 2004) and is attributed primarily to the homogeneity of unsaturated zone conditions (unconsolidated aeolian sands with little opportunity for preferential flow), land cover and climate over the study area. Results also indicate that topography has no impact on recharge variability and that topographic depressions in the dune complex do not result in focused recharge.

Mean Cl varied among the profiles from 62 to 164 mg/L, and an average diffuse recharge rate of 1.0–3.6 mg/L

Table 4 Published data for groundwater Cl concentrations in the study area

Location	Cl (mg/L)	Source
Yindertu	87	Yang and Williams 2003
Nouertu	94	Yang and Williams 2003
Nouertu	64	Hofmann 1999
Nouertu	69	Hofmann 1999
Nouertu	63	Hofmann 1999
Baoritelegai	234	Ma and Edmunds 2006
Baoritelegai	122	Ma and Edmunds 2006
Baddam	202	Yang and Williams 2003
Baddam	383	Ma and Edmunds 2006
Baddam	118	Hofmann 1999
Baddam	215	Hofmann 1999

 DOI 10.1007/s10040-007-0264-z

was estimated. The ratio of diffuse recharge to annual precipitation observed in the Badain Jaran Desert (~1:100) is globally common for areas with dry, sandy conditions. A positive relationship between vegetation density and Cl content was shown for the few profile locations with relatively high vegetation densities, though no correlation was discernable for lower densities. No relationship was found between Cl content and topographic setting, position relative to megadunes, elevation, or geographic grouping. Vertical fluctuations in Cl concentrations indicate temporal variations in recharge, and similar fluctuations are common to many profiles.

Based on water-balance considerations, direct recharge through the unsaturated zone is insufficient to support the study area's network of groundwater-fed perennial lakes. This conclusion contradicts previous suggestions put forward by several other workers over the last decade, but is consistent with the recent findings of Ma and Edmunds (2006) and the growing body of evidence that shallow groundwaters within the Badain Jaran Desert are palaeowaters recharged during the late Pleistocene or wetter climatic periods within the Holocene. Further refinement of the hydrological conceptual model is needed to support sustainable water management strategies for this region of high ecological and growing economic importance.

Acknowledgements The research is supported by the National Science Foundation of China (No. 40671029), the Dudley Stamp grants programme of the Royal Society, and a postgraduate research grant from the British Society for Geomorphology. This work also forms part of a wider UK-China collaboration and we acknowledge the support of the Royal Society through its link scheme (PEK/0992/306). The authors would like to thank H. Tianming, L. Xianghu and D. Zhenyu for field and laboratory support, and P. Renard, S. Yonghong, I. Cartwright and an anonymous reviewer for helpful comments on the manuscript.

References

Allison GB, Hughes MW (1978) The use of environmental tritium and chloride to estimate total recharge to an unconfined aquifer. Australian J Soil Sci 16:181–195

Allison GB, Stone WJ, Hughes MW (1985) Recharge in karst and dune elements of a semi-arid landscape by natural isotopes and chloride (Murray Basin, Australia). J Hydrol 76(1–2):1–25

Allison GB, Cook PG, Barnett SR, Walker GR, Jolly ID, Hughes MW (1990) Land clearance and river salinisation in the western Murray Basin, Australia. J Hydrol 119:1–20

An C, Feng Z, Barton L (2006) Dry or humid? Mid Holocene humidity changes in arid and semi-arid China. Quat Sci Rev 25 (3–4):351–361

Boulton AJ, Humphreys WF, Eberhard SM (2003) Imperilled subsurface waters in Australia: biodiversity, threatening processes and conservation. Aquat Ecosyst Health Manage 6 (1):41–54

Brunner P, Bauer P, Eugster M, Kinzelbach W (2004) Using remote sensing to regionalize local precipitation recharge rates obtained from the Chloride Method. J Hydrol 294(4):241–250

Chen JS, Li L, Wang JY, Barry DA, Sheng XF, Gu WZ, Zhao X, Chen L (2004) Groundwater maintains dune landscape. Nature 432:459–460

Cook PG, Edmunds WM, Gaye CB (1992) Estimating paleorecharge and paleoclimate from unsaturated zone profiles. Water Resour Res 28(10):2721–2731

de Vries JJ, Simmers I (2002) Groundwater recharge: an overview of processes and challenges. Hydrogeol J 10(1):5–17

Dettinger MD (1989) Reconnaissance estimates of natural recharge to desert basins in Nevada, USA, by using chloride balance calculations. J Hydrol 106(1–2):55–78

Domros M, Peng G (1988) The climate of China. Springer Netherlands, Dordrecht, The Netherlands

Dong Z, Wang T, Wang X (2004) Geomorphology of the megadunes in the Badain Jaran Desert. Geomorphology 60(1–2):203

Dyck MF, Kachanoski RG, de Jong E (2005) Spatial variability of long-term chloride transport under semiarid conditions. Vadose Zone J 4:915–923

EANET (2006) EANET data on the acid deposition in the East Asian region. Acid Deposition and Oxidant Research Center, Niigata-shi, Japan. http://www.eanet.cc. Cited 15 Feb 2007

Edmunds WM, Gaye CB (1994) Estimating the spatial variability of groundwater recharge in the Sahel using chloride. J Hydrol 156 (1–4):47–59

Edmunds WM, Darling WG, Kinniburgh DG (1988) Solute profile techniques for recharge estimation in semi-arid areas and arid terrain. In: Simmers I (ed) Estimation of natural groundwater recharge. Reidel, Dordrect, The Netherlands, pp 139–157

Edmunds WM, Fellman E, Goni IB, Prudhomme C (2002) Spatial and temporal distribution of groundwater recharge in northern Nigeria. Hydrogeol J 10(1):205–215

Edmunds WM, Ma J, Aeschbach-Hertig W, Kipfer R, Darbyshire F (2006) Groundwater recharge history and hydrogeochemical evolution in the Minqin Basin, north west China. Appl Geochem 21(12):2148–2170

Favreau G, Leduc C, Marlin C, Dray M, Taupin JD, Massault M, La Salle CL, Babic M (2002) Estimate of recharge of a rising water table in semiarid Niger from H-3 and C-14 modeling. Ground Water 40:144–151

Feng Q, Liu W, Su YH, Zhang YW, Si JH (2004) Distribution and evolution of water chemistry in Heihe River basin. Environ Geol 45:947–956

Gieske A, Selaolo E, McMullen S (1990) Groundwater recharge through the unsaturated zone of southeastern Botswana: a study of chloride and environmental isotopes. IAHS Publ no. 191, IAHS, Wallingford, UK, pp 33–44

Goni IB, Fellman E, Edmunds WM (2001) Rainfall geochemistry in the Sahel region of northern Nigeria. Atmos Environ 35 (25):4331–4339

Hayashi M, van der Kamp G, Schmidt R (2003) Focused infiltration of snowmelt water in partially frozen soil under small depressions. J Hydrol 270:214–229

Heilweil V, Solomon K (2004) Millimeter- to kilometer-scale variations in vadose-zone bedrock solutes: implications for estimating recharge in arid settings. In: Hogan JF, Phillips F, Scanlon BR (eds) Groundwater recharge in a desert environment: the southwestern United States. American Geophysical Union, Washington, DC, pp 49–67

Hofmann J (1996) Lakes in the SE part of Badain Jaran Shamo, their limnology and geochemistry. Geowissenschaften 14(7–8):275–278

Hofmann J (1999) Geoökologische Untersuchungen der Gewässer im Südosten der Badain Jaran Wüste [Geoecological studies of the waters of the southeastern Badain Jaran Desert]. Berliner Geograph Abhandl 64:1–247

Jäkel D (1996) The Badain Jaran Desert: its origin and development. Geowissenschaften 7–8:272–274

Jäkel D (2002) The importance of dunes for groundwater recharge and storage in China. Z Geomorph NF Suppl 126:131–146

Jäkel D (2004) Initial stages of complex duneforms after rainfall and formation processes of honeycomb and kettle dunes in the Badain Jaran Desert (Shamo) in China. Z Geomorph NF Suppl 133:107–128

Johnston C (1987) Preferred water flow and localized recharge in a variable regolith. J Hydrol 94:129–142

Keese KE, Scanlon BR, Reedy RC (2005) Assessing controls on diffuse groundwater recharge using unsaturated flow modeling. Water Resour Res 41(6):W06010

 DOI 10.1007/s10040-007-0264-z

Lundin LC (1990) Hydraulic properties in an operational model of frozen soil. J Hydrol 118:289–310

Ma J, Edmunds WM (2006) Groundwater and lake evolution in the Badain Jaran desert ecosystem, Inner Mongolia. Hydrogeol J 14 (7):1231–1243

McCord JT, Stephens DB (1987) Lateral moisture flow beneath a sandy hillslope without an apparent impeding layer. Hydrol Process 1:225–238

Mischke S, Demske D, Wünnemann B, Schudack M (2005) Groundwater discharge to a Gobi desert lake during Mid and Late Holcene dry periods. Palaeogeogr Palaeoclimatol Palaeoecol 225(1–4):157–172

Murphy EM, Ginn TR, Phillips JL (1996) Geochemical estimates of paleorecharge in the Pasco Basin: evaluation of the chloride mass balance technique. Water Resour Res 32(9):2853–2868

Petheram C, Walker G, Grayson R, Thierfelder T, Zhang L (2002) Towards a framework for predicting impacts of land-use on recharge: 1. a review of recharge studies in Australia. Aust J Soil Res 30(3):397–417

Phillips F (1994) Environmental tracers for water movement in desert soils of the American Southwest. Soil Sci Soc Am J 58:14–24

Prych EA (1998) Using chloride and chlorine-36 as soil-water tracers to estimate deep percolation at selected locations on the US Department of Energy Hanford Site, Washington. US Geol Surv Water Suppl Pap 2481

Scanlon BR (1991) Evaluation of moisture flux from chloride data in desert soils. J Hydrol 128(1–4):137–156

Scanlon BR, Goldsmith RS (1997) Field study of spatial variability in unsaturated flow beneath and adjacent to playas. Water Resour Res 33(10):2239–2252

Scanlon BR, Keese K, Reedy RC, Simunek J, Andraski BJ (2003) Variations in flow and transport in thick desert vadose zones in response to paleoclimatic forcing (0–90 kyr): field measurements, modeling, and uncertainties. Water Resour Res 39:1179. DOI 1110.1029/2002WR001604

Scanlon BR, Reedy RC, Stonestrom DA, Prudic DE, Dennehy KF (2005) Impact of land use and land cover change on groundwater recharge and quality in the southwestern USA. Glob Chang Biol 11:1577–1593

Selaolo E, Gieske A, Beekman H (1994) Chloride deposition and recharge rates for shallow groundwater basins in Botswana. Paper presented at Water Down Under 94, Institute of Engineers, Adelaide, Australia, November 1994, vol 2(B), pp 501–506

Sharma M, Hughes MW (1985) Groundwater recharge estimation using chloride, deuterium and oxygen-18 profiles in the deep coastal sands of Western Austrialia. J Hydrol 81(1–2):93–109

Sophocleous M (1992) Groundwater recharge estimation and regionalization: the Great Bend Prairie of central Kansas and its recharge statistics. J Hydrol 137(1–4):113–140

Stahli M, Jansson PE, Lundin LC (1996) Preferential water flow in a frozen soil: a two-domain model approach. Hydrol Process 10:1305–1316

Stone WJ (1992) Paleohydrologic implications of some deep soil water chloride profiles, Murray Basin, South Australia. J Hydrol 132:201–223

Tyler SW, Chapman JB, Conrad SH, Hammermeister DP, Blout DO, Miller JJ, Sully MJ, Ginanni JM (1996) Soil-water flux in the southern Great Basin, United States: temporal and spatial variations over the last 120 000 years. Water Resour Res 32 (6):1481–1499

Walvoord MA, Phillips FM (2004) Identifying areas of basin-floor recharge in the Trans-Pecos region and the link to vegetation. J Hydrol 292(1–4):74

Yan M, Wang S, Li B, Dong G (2001) Formation and growth of high megadunes in Badain Jaran Desert. Acta Geogr Sin 56:83–91

Yang X, Williams MAJ (2003) The ion chemistry of lakes and late Holocene desiccation in the Badain Jaran Desert, Inner Mongolia, China. Catena 51(1):45–60

Zhang H, Peng J, Ma Y, Chen G, Feng Z, Li B, Fan H, Chang F, Lei G, Wünnemann B (2004) Late Quaternary palaeolake levels in Tengger Desert. Palaeogeogr Palaeoclimatol Palaeoecol 211(1–2):45–58

Zhao LT, Gray DM (1997) A parametric expression for estimating infiltration into frozen soils. Hydrol Process 11:1761–1775

 DOI 10.1007/s10040-007-0264-z