Determining groundwater degradation from irrigation in desert-marginal northern China

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Abstract

Groundwater degradation from irrigated agriculture is of concern in semi-arid northern China. Data-scarcity often means the causes and extent of problems aren't fully understood. This study investigated an irrigated area in Inner Mongolia where abstraction from an unconfined Quaternary aquifer has increased threefold over 20 years to 20 Mcm/yr; groundwater levels are falling at up to 0.5 m/yr; and groundwater is increasingly mineralised (TDS increase from 400 mg/L to 700–1900 mg/L), with nitrate concentrations up to 137 mg/L-N. Residence-time (chlorofluorocarbon/CFC), stable-isotope and hydrogeochemical indicators helped develop a conceptual model of groundwater system evolution, demonstrating a direct relationship between modern water proportion and the degree of groundwater mineralisation, indicating that irrigation water recycling is reducing groundwater quality. The investigations suggest that before irrigation development, active recharge to the aquifer from wadis significantly exceeded groundwater inflow from nearby mountains, previously held to be the main groundwater input. Away from active wadis, groundwater is older with a probable pre-Holocene component. Proof-of-concept groundwater modelling supports geochemical evidence, indicating the importance of wadi recharge and irrigation return flows. Engineering works protecting the irrigated area from flooding have reduced good quality recharge; active recharge is now dominated by irrigation returns, which are degrading the aquifer.

Introduction

Groundwater is the primary source of water in most of arid northern China, with the largest use being for irrigation (Kendy et al. 2003). Low rainfall and high evapotranspiration mean surface water resources are scarce. Groundwater is subject to increasing abstraction pressure as a result of rapid population and economic growth (e.g. Foster et al. 2004, Ji et al. 2006).

The detrimental impacts of irrigated agriculture on groundwater resources in northern China are widely recognised (Foster et al 2004, Ma et al 2005, Ji et al 2006). Intensive abstraction has caused widespread water table decline, such as in parts of the North China Basin, where Kendy et al. (2003) report that groundwater levels are falling by more than 1.0 m/yr. Severe groundwater quality degradation has also occurred beneath many irrigated areas, linked to the recycling of salts from irrigation water, and particularly to nitrate from intensive fertiliser use (e.g. Chen et al. 2005, Ji et al. 2006). As water tables fall, groundwater abstraction becomes more difficult and expensive, and eventually wells may dry up. As its quality deteriorates, groundwater may become unsuitable for higher quality uses.

This paper investigates the causes and impacts of groundwater degradation in a Quaternary aquifer in an irrigated area, Chahaertan, in Inner Mongolia in northern China. Few groundwater data are available for this region, and to address this, a range of hydrogeological techniques was applied to investigate and interpret the local groundwater system and how it has developed historically in response to the expansion of abstraction for irrigation. This approach, particularly related to groundwater residence times and the historical development of groundwater systems, complements the recently growing body of hydrogeological work in China by advancing the focus on managing groundwater resources and irrigated agriculture.

The Chahaertan irrigated area lies between longitude 105° 37’ to 105° 45’ E and latitude 39° 14’ to 39° 29’ N, at an elevation of between 1100 and 1200 m above sea level (asl) (Figure 1). This region, near the eastern edge of the Tengere desert, is semi-arid and characterised by low, irregular rainfall and high temperatures and evapotranspiration (Ma et al. 2005). Land use is dominated by scrub grassland, much of it degraded, and sandy desert, with some limited forest cover. Areas under irrigation, such as Chahaertan, account for a small proportion of the total land area, but are significant in terms of human and economic activity. At Chahaertan, more than 150 wells support intensive seasonal groundwater abstraction to irrigate commercial crops: dominantly maize, sunflowers and watermelon, with increasing amounts of cotton. Almost all groundwater abstraction is for irrigation and occurs between April and August. Away from the irrigated area there are only a handful of wells across the rest of the Quaternary aquifer, which abstract at low rates for domestic and small-scale livestock use.

By the mid 2000s it was suspected that intensive abstraction at Chahaertan was having a detrimental effect on the groundwater resource. However, because no monitoring or investigations had been carried out since the mid 1990s (Yuan and Wu 1996), a lack of hydrogeological data and understanding precluded the establishment of an effective management strategy. The common theory at this time held that the major groundwater input to the local Chahaertan system was slow lateral flow through the aquifer from its southern boundary, where focussed recharge occurred from surface water flowing from the Helan Mountains (Figures 1 and 2) (Yuan and Wu 1996). However, this did not explain many of the observed system features.

New groundwater investigations

In 2006 an investigation was carried out at Chahaertan to collate existing and collect new essential information and improve understanding of the groundwater system and the state of the groundwater resource, and to provide the basis for effective resource management. To deal with the lack of historical hydrogeological and hydrological data, a set of complementary hydrogeological and hydrogeochemical techniques, including detailed groundwater residence time analysis using CFCs, was used to establish a comprehensive picture of the groundwater system.

More than 150 abstraction wells in Chahaertan were accurately located using GPS, and a questionnaire used to collect information from well owners to help document historical groundwater development and estimate current groundwater abstraction.

Historical groundwater level measurements were located for six monitoring wells in the main irrigated area for the period 1984–94, and new measurements made in these wells in September 2006. All are close to abstraction wells and affected by pumping. Additional water level measurements were made in abstraction wells across the irrigated area. Outside this area there are limited historical data for the Quaternary aquifer, but what were available were collated from hydrogeological maps and reports, and where possible new measurements were also made in available (usually pumping) wells.

Meteorological data were obtained from government meteorological records and research stations, published reports, and previous studies (e.g. Yuan and Wu 1996, People's Liberation Army 1976 and 1980). Additional information on aquifer geology, geometry and hydraulic properties, and well yields was collated from records, reports and maps from a variety of sources (e.g. People's Liberation Army 1976, 1980; Left Banner Water Management and Water Resource Office 1992; Yuan and Wu 1996).

Twenty two groundwater samples were collected from the Quaternary aquifer: 19 from the irrigated area (including two from a separate zone to the north of the main irrigated area, called Little Chahaertan), and three from the surrounding un-irrigated aquifer (Figure 3). All except one of the samples were collected from pumped abstraction wells, the remaining one being collected from a flowing artesian well. Technical details of sample collection are given in Ó Dochartaigh and MacDonald (2006). Proof of concept numerical modelling was used to test the results of the hydrodynamic and hydrogeochemical (including residence time) analysis and the conceptual understanding of the groundwater system.

The hydrogeology of Chahaertan and the development of irrigation and the groundwater system

Irrigation wells at Chahaertan abstract from an unconfined Quaternary alluvial aquifer infilling a faulted basin in Cretaceous and Tertiary rocks. The southern edge of the aquifer basin is faulted against the Helan Mountains, ~30 km southeast of Chahaertan; the northern boundary of the groundwater catchment is at Jilantai lake, ~35 km north of Chahaertan, which is the main discharge point for surface water and groundwater in the catchment (Figure 1). The total groundwater catchment area is ~1500 km^2. Aquifer thickness varies from less than 30 m at its southern edge to more than 200 m around Chahaertan (Figure 2), and possibly deeper at Jilantai. Surface elevation ranges from over 3000 m asl at the top of the Helan Mountains to 1000 m asl at Jilantai. Near to Jilantai the aquifer becomes confined in some areas. The exact extent of artesian conditions is unknown, but the approximate extent has been estimated (Figure 1) by the presence of vegetation and salt encrustation in unirrigated areas visible on satellite imagery.

Basin infill is dominated by fluvial sediment eroded from the Helan Mountains and transported northwestwards by high-energy ephemeral rivers (wadis) (Figure 2). Previous studies showed that aquifer hydraulic properties are strongly influenced by sediment grain size variation, with generally coarser-grained deposits proximal to the Helan Mountains showing a transmissivity range of 600 to 1200 m^2/d, and finer-grained distal deposits around Chahaertan a range of 200 to 510 m^2/d (Groundwater Development and Utilisation Teaching and Research Office 1984, Yuan and Wu, 1996). There are no available data on aquifer mineralogy.

Outside the irrigated area there is little soil development, and the region is dominated by sand with thin scrub vegetation. Prior to irrigation development, however, seasonal overbank flooding at Chahaertan at the confluence of wadis draining the Helan Mountains led to significant soil development (Groundwater Development and Utilisation Teaching and Research Office 1984, Jerie 2006).

Long-term average (LTA) rainfall at Chahaertan is some 200 mm/yr; over the Helan Mountains to the south it is 400 mm/yr, falling to 100 mm/yr at Jilantai to the north. Most precipitation falls between June and September as short-lived intensive events. Mean annual potential evaporation ranges from 1400 mm in the mountains to 3000 mm at Jilantai, and is highest between May and August. The temperature at Chahaertan exceeds 30°C in summer but is typically below 0°C in winter, with an annual mean of ~15°C (e.g. Yuan and Wu 1996, People's Liberation Army 1976 and 1980).

There is no permanent surface water drainage. Wadis drain runoff from the Helan Mountains northwest towards Jilantai, four of which converge to the south of Chahaertan, from where a single channel flows north to Jilantai. No river flow monitoring is carried out in the region, but there is anecdotal evidence for channel flows at Chahaertan and Jilantai. Based on this and on the size of the river channel, gradient and depth (Table I), the river flow rate during these events is estimated at between 20 and 30 m^3/sec.

Overall groundwater flow direction in the Quaternary is from the south and southeast to the north. Natural groundwater discharge is to the lake at Jilantai and to springs and seepages in this area, seen in the distribution of artesian conditions (Figure 1). At Chahaertan, groundwater flows are likely to be influenced by local indirect recharge and by intensive groundwater abstraction.

Since initial development in the late 1960s, the number of abstraction wells, volume of groundwater abstraction, and irrigated area at Chahaertan have increased markedly (Figure 4) (data from Groundwater Development and Utilisation Teaching and Research Office 1984, Left Banner Water Management and Water Resource Office 1992). Since 1990, most new wells have been drilled in Little Chahaertan, just north of the main irrigated area (Figure 4).

In 2006 groundwater levels ranged from 45 m below ground level (mbgl) at the northern edge of the main irrigated area to more than 75 mbgl some 8.5 km away in the south, this slope being largely controlled by topography. The only available historical monitoring data show that groundwater levels in this area fell by an average of 0.5 m/yr between 1984 and 1995, a decline that apparently continued until 2006, albeit at a slightly slower rate (Figure 4). This is likely to be linked to the slow-down in the rate of increase of abstraction in this area after the shift in focus for groundwater development to Little Chahaertan (where there has been no groundwater level monitoring) after 1990.

Regular groundwater quality monitoring has never been undertaken at Chahaertan, but the limited available data indicate that pre-development groundwater chemistry is likely to have been similar to groundwater today in the surrounding non-irrigated area: moderately mineralised, Ca-Mg dominated waters with slightly alkaline pH, and less than 5 mg/L NO_3-N. By 2006, TDS concentrations in the irrigated area were between 700 and 1900 mg/L, and nitrate concentrations reached up to 137 mg/L as N. Nitrogen isotope analysis has shown that the bulk of this nitrate derives from fertiliser (Jerie 2006).

Irrigation development at Chahaertan was heavily dependent on its position at the confluence of four wadis and consequent local seasonal overbank flooding and soil development (Groundwater Development and Utilisation Teaching and Research Office 1984). Since development, however, the wadi channels have been engineered, including major re-routing of the original confluent channel from the centre to the western edge of the irrigated area, which has largely prevented flooding, and consequent crop and livelihood damage, in the now intensively farmed area.

Groundwater chemistry

An understanding of groundwater chemistry has been critical in revealing changing recharge processes at Chahaertan. Groundwater chemistry has been interpreted from the 22 samples collected from abstraction wells in the irrigated area and surrounding region. The average length of the screened section of the production wells from which samples were collected is 45 m (Left Banner Water Management and Water Resource Office 1992). The locations and field measurements of chemistry samples are given in Table ESM1, and locations are shown in Figure 3. Major and minor inorganic species are reported in Table ESM2. Stable isotope and CFC analyses are provided in Table ESM3.

Pre-development groundwater chemistry

The nature of an intensively irrigated area means that little groundwater is likely to be fully representative of pre-development water quality, and therefore of natural processes operating along the groundwater flowline. No pre-development chemistry data for the aquifer are available, but seven of the new groundwater samples are likely to represent quasi-natural conditions. Three of these (Sites 20, 21 and 22) are away from any irrigation and outside the local Chahaertan groundwater system; four (Sites 4 and 16 in Chahaertan, and 18 and 19 in Little Chahaertan) are within the irrigated area (Figure 3). Site 22, away from any irrigation and unlikely to be influenced by agricultural or other contamination, has a NO_3-N concentration of 5.6 mg/L and a TDS of ~450 mg/L. This is likely to be indicative of pre-development chemistry: arid area groundwaters frequently have detectable NO_3-N originating from sources such as atmospheric deposition, bacteria in soil crusts, and termite mounds (Gates et al. 2008). All four probable quasi-natural groundwater samples within the irrigated area show similar NO_3-N concentrations of <5 mg/L.

These pre-development groundwaters are Ca-Mg dominated and moderately mineralised, with an average TDS of 395 mg/L, well oxygenated, with a slightly alkaline pH, and noticeably lower concentrations of all major ions (except HCO_3), than the other Chahaertan waters (Tables ESM1, ESM2). They are comparable to a similar Quaternary alluvial aquifer in the semi-arid Datong Basin in northwest China, where groundwaters unaffected by agriculture or industry had an average TDS of < 300 mg/l and NO_3-N concentration of 7.3 mg/l (Guo and Wang 2004).

The sampled wells consistently show evolution in key species in the downstream flow direction from Chahaertan to Jilantai (Figure 5). The increase in Na as Ca decreases is typical of ion exchange, but the greater magnitude of Na enrichment compared to the Ca decline (Figure 6a) suggests an additional source of Na. Evidence from Br/Cl ratios (Figure 6b) indicates this could be halite dissolution, but in the absence of any mineralogical data for the aquifer this cannot be confirmed. From Site 19 northwards, Cl and SO_4 concentrations increase at the expense of HCO_3. The increase in Cl is consistent with halite dissolution. The SI_{gypsum} values are two orders of magnitude below saturation (Table ESM2), indicating gypsum dissolution as the cause of the increase in SO_4. The excess Ca initially produced may have been taken up by ion exchange and/or precipitation of calcite due to solubility considerations.

Irrigation-related changes to groundwater chemistry

Sites 1–17 are all within the main irrigated area and all show evidence of irrigation-related changes in groundwater chemistry (excluding Sites 4 and 16 discussed above). The groundwaters are well-oxygenated, with pH values in the range 7.4–8.0, and are significantly more mineralised than the pre-development group, with an average TDS of 1156 mg/L, and generally at least double the concentrations of major ions (Table ESM2). The average NO_3-N concentration is 27.9 mg/L, more than seven times that of the average in the pre-development group. This compares with evidence from similar irrigated aquifers in northwest China, where TDS is >800 mg/L and NO_3-N >23 mg/L (Guo and Wang 2004).

Multi-plots versus Cl of the main ions (Figure 7) show generally good correlations, positive for Ca, Na and SO_4, and negative for HCO_3, with Site 4 (quasi-natural water) having the least-modified composition. The linear increases can be attributed to the effects of groundwater mixing with evaporated irrigation return water. The decrease in HCO_3 is consistent with the loss of CO_2 during recycling, and therefore a tendency towards calcite precipitation, supported by the positive correlation ($r^2 = 0.44$) between $SI_{calcite}$ and pH (Table ESM2). Nitrate has the poorest correlation with Cl, which is probably a consequence of biotic effects.

Groundwater residence time

Pre-development groundwater residence times

CFC analyses are only available for two pre-development samples: Sites 4 and 19 (Table ESM3). CFC-11 and CFC-12 are both below detection at Site 19 in Little Chahaertan, indicating no evidence of modern water. This is likely to reflect the smaller influence of focussed recharge from pre-development overbank flooding north of the main Chahaertan area (Figure 1). Site 4 shows evidence of modern water, indicating active modern recharge, which is likely to derive largely from pre-development flooding and leakage through wadi beds. Recharge modelling to confirm this hypothesis is discussed in a subsequent section.

Stable isotopes in groundwaters from Chahaertan are too depleted to represent local groundwater recharge from modern rainfall at this altitude. The presence of CFCs and the fact that stable isotopes at Site 4 are less depleted than in the likely pre-Holocene waters further north along the flow line (Sites 18 and 20; Figure 8), imply that pre-development groundwater at Chahaertan is not particularly old, and unlikely to be pre-Holocene. The isotopic composition of end-Pleistocene groundwater is based on a 2‰ depletion in $\delta^{18}O$, as found by Kreuzer et al. (2009) in the North China Plain (Figure 8). The most likely source of recharge is rainfall runoff from the Helan Mountains, where the higher altitude creates cooler recharge conditions. The likely presence of pre-development modern water at Chahaertan implies the recharge route is local river infiltration, as the travel time for groundwater flow to Chahaertan from recharge at the edge of the mountains is estimated at ~5kyr, based on reported or estimated aquifer hydraulic properties and Darcy's law (assuming a hydraulic gradient of 0.003 (Yuan and Wu 1996) and a hydraulic conductivity of 5 m/d).

When interpreting the patterns in CFC-12 and $\delta^{18}O$ in downgradient samples (Figure 9) in terms of an evolutionary sequence, key evidence is the below detection CFC-12 at Site 20, some 30 km north of

Chahaertan, and the presence of well oxygenated water, which argues against any microbial degradation (e.g. Busenberg and Plummer 1992). It is therefore assumed that groundwater at Site 20 is more than 50 years old, which suggests that the main recharge area is at Chahaertan, with no modern recharge downgradient of Chahaertan. This is supported by $\delta^{18}O$ values, which show a steady declinebetween Sites 4 and 20, of the order of 2 ‰, indicating that the flowline is long enough to retain some Pleistocene (>10 kyr) water in the system. By comparison, in the North China Plain similar depletions in $\delta^{18}O$ were observed for late Pleistocene palaeowaters (Chen et al. 2003).

However, the data for Site 21 at Jilantai indicate a proportion of modern water is present (Figure 9). This borehole is drilled beneath Jilantai lake, and groundwater abstracted from the borehole is discharged into the lake, which is likely to locally reverse the hydraulic gradient and cause some re-infiltration of lake water into the aquifer.

Irrigation-related changes to groundwater residence

CFC data indicate that most of the sampled groundwaters have a modern water component of 5–10%. A plot of CFC-11 versus CFC-12 concentrations is superimposed with the expected 'piston flow' concentration curve relating to the year of recharge and the expected mixing line between modern and older CFC-free water (Figure 10). In practice, where the two lines are close together it is impossible to discriminate between piston flow and mixing. Additionally, there is evidence for a small amount of CFC-12 contamination in some samples, most notably Sites 1 and 4. The alternative explanation of CFC-11 reduction is unlikely based on the observed positive dissolved oxygen concentrations. Modern recharge could be from two sources: wadi flow or irrigation return water (which would acquire a modern CFC load while exposed to the atmosphere). The positive correlation between CFC-11 (presumed to be uncontaminated) and TDS (total dissolved solids) (Figure 11) suggests that irrigation return water is the more likely source. Site 4 lies outwith this trend, indicating that it is not impacted by irrigation returns, and further supporting its quasi-natural status.

Stable isotopes from Chahaertan groundwaters are tightly grouped (the standard deviation on $\delta^{18}O$ is 0.22 ‰), but the average is slightly beneath the Yinchuan meteoric line (Figure 8). This suggests there has been minor evaporative fractionation, consistent with the evidence of recycling demonstrated by the groundwater chemistry and CFCs. The average composition, at around –11 ‰ $\delta^{18}O$ and –80 ‰ $\delta^{2}H$, is significantly depleted compared to the Yinchuan average (Figure 8). Since Yinchuan is at an elevation of 1100 m asl, similar to Chahaertan, this implies the source of recharge at Chahaertan lies at a significantly higher altitude. The hydrodynamic factors of the system mean this source can only be the Helan Mountains, as for the pre-development water. This has subsequently been recycled as irrigation water.

Testing results using groundwater modelling

Proof of concept numerical modelling was used to test the results of the hydrodynamic and hydrogeochemical (including residence time) analysis and the conceptual understanding of the groundwater system. The scarcity of hydrogeological data and, therefore, limited conceptual understanding, means that numerical modelling can only support the development of the understanding of the groundwater system. It cannot provide a detailed simulation of the system (for example, for use as a management tool for assessing the impact of individual production wells) without significantly more information than is currently available.

Model set up

Modelling was undertaken using the ZOOM (Zoomable Object Oriented Model) suite of object-oriented numerical groundwater models (Spink et al. 2003; Spink et al. 2006). This includes a distributed recharge model, ZOODRM (Zoomable Object Oriented Distributed Recharge Model) (e.g. Hughes et al. 2006, Hughes et al. 2008), which calculates spatial and temporal variations in groundwater recharge, incorporating a standard Penman-Grindley type soil moisture balance method, the modified FAO Penman-Monteith method (Allen et al. 1998), and procedures for recharge estimation in arid countries (a “Wetting Threshold” method based on the work of Lange et al., 2003; Hughes et al., 2008) and irrigated regions, as well as surface runoff routing. The ZOOM suite also includes a groundwater flow model, ZOOMQ3D (Zoomable Object Oriented Model for Quasi-Three Dimensional Flow) (e.g. Jackson et al. 2005), which incorporates mesh refinement to aid the solution of scale-related problems, and is based on object-oriented techniques.

A detailed description of model development and input parameters is given in Ó Dochartaigh and MacDonald (2006). A distributed recharge model was developed encompassing the Quaternary aquifer catchment and the surface water catchment on the northern side of the Helan Mountains that drains towards Jilantai, taking into account the discharge zone in the area around Jilantai (Figure 12). The model area is 43 km by 83 km (Figure 12) with a cell size of 1000 m. Using data on daily rainfall, potential evaporation, land-use and topography, the model simulates LTA recharge based on average climatic data for the periods 1955-1980 and 2003-2005. It uses a wetting threshold method that is appropriate to arid and semi-arid conditions (Lange et al. 2003, Hughes et al. 2008). Two zones for wetting threshold were chosen: the outcrop of Quaternary and Tertiary age rocks. Indirect recharge was provided by including run-off processes to the wadis deriving the aspect direction from the DEM. Further information on the recharge model boundary conditions, model parameters, input and output and validation data is presented in Table ESM4.

A steady state groundwater flow model was developed to encompass the Quaternary basin aquifer within the Jilantai catchment area (Figure 12), simulating the groundwater system for a single year under 2006 conditions (Figure 13), and using calculated LTA recharge from the distributed recharge model. The groundwater flow model is a single layer model with an identical size and mesh to the recharge model. Inflows are rainfall recharge, indirect recharge from wadis and irrigation returns, which are provided directly from the recharge model. Outflows are from abstractions and groundwater discharge to the Jilantai Lake. Transmissivity and storage coefficients are distributed based on information from the available literature (e.g. Groundwater Development and Utilisation Teaching and Research Office, 1984). Further information on the groundwater flow model boundary conditions, model parameters, input and validation data is presented in Table ESM5. Subsequently, a dynamic balance groundwater flow model was developed to investigate the time variant nature of the system, representing a 30 year period from 1980 to 2010, and using monthly varying recharge from the recharge model (Table ESM5). A dynamic balance is achieved by inputting a repeated annual series of average monthly recharge. The repeated annual series is run through the model until the groundwater heads in each month are identical to those in the same month in the previous year (Rushton and Wedderburn 1971).

Model results

The recharge model was refined so the simulated river flows fit closely the available estimates of actual wadi flows across the aquifer. Little river water is lost as wadis flow over non-aquifer rocks, but losses through wadi floors occur across the Quaternary aquifer. The rate of modelled wadi recharge depends on the volume and duration of wadi flows, and is highest along the southwest and western edges of the main irrigated area (Figure 12). There is little wadi recharge north of Chahaertan, where the river channel usually flows only once or twice a year, and at a lower rate. Modelled recharge volumes are shown in Table II and indicate that wadi losses and irrigation returns provide the majority of recharge to the entire Quaternary aquifer, and dominate recharge in the vicinity of Chahaertan.

The steady state groundwater flow model, with input from the recharge model and available aquifer parameters, represents the groundwater head distribution across the aquifer relatively closely (Figure 13). This improves confidence in our understanding of the Chahaertan groundwater system, supporting the limited available hydrogeological data and implying that the recharge and flow processes inferred from hydrodynamic and hydrogeochemical (including residence time) analysis are plausible. Although the lack of data, and in particular daily rainfall, means that fully a refined historical simulation is not yet possible, a dynamic balance model reproduces the general pattern of observed annual groundwater level variations and the observed groundwater level fall over the period of irrigation development, further improving confidence in our understanding of the groundwater system (Ó Dochartaigh and MacDonald 2006). If the decline continues at the same rate, production wells may start to show falling yields within 20 to 30 years, and the shallowest wells (100 m deep) may need to be abandoned within 40 years.

Discussion

The combined study of hydrodynamics, hydrochemistry (including residence times) and subsequent testing with a groundwater recharge and flow model has helped unravel the processes of groundwater degradation in the Chahaertan irrigated area. Of particular importance is the change in recharge processes during the development of the area.

Predevelopment

Before irrigation development at Chahaertan, surface and groundwater flowed largely uninterrupted from the Helan Mountains to the Jilantai lake. The presence of CFC, isotopic signature, and lack of increased salinity in pre-development groundwater at Chahaertan indicate that active local wadi recharge occurred within the last 50 years, and before the onset of irrigation returns in the late 1970s. Model results confirm that infiltration occurred along the wadi channels between the Helan Mountains and Chahaertan, but was significantly enhanced at Chahaertan. This was caused by annual overbank flooding, which helped develop the soils that support agriculture Chahaertan. This study is the first to emphasise the importance of local recharge at Chahaertan. Previous theories held that most recharge to the aquifer basin occurred at the edge of the Helen Mountains, with subsequent slow subsurface flow to Chahaertan over thousands of years. The new modelling and geochemical studies show that, although this mechanism may be occurring, it is not the dominant influence on the groundwater system.

Groundwater modelling indicates that from Chahaertan northwards, subsurface flow dominates water movement to Jilantai. This is corroborated by residence time data, as groundwater further down the flow line does not show detectable CFCs, and there is no evidence of active recharge for at least the past 50 years. The depletion in δ^2H and $\delta^{18}O$ in groundwaters is likely to be the product of mixing between a late-Pleistocene end-member, with a depleted isotopic composition indicating cooler recharge conditions, and younger Holocene water (up to 10 kyr) old that has an essentially modern isotopic composition. This is similar to results from other parts of northern China (e.g. Chen et al 2003, Ma and Edmunds 2006), and is consistent with modelled groundwater travel times thousands of years through the aquifer to Jilantai. The one exception is at Jilantai lake itself, where mixing with re-infiltrating lake water appears to have led to the presence of CFCs in groundwater.

Pre-development groundwater chemistry at Chahaertan is likely to have been similar to that of groundwater today in the surrounding non-irrigated area: moderately mineralised (TDS ~400 mg/L), Ca-Mg dominated waters with slightly alkaline pH, and less than 5 mg/L NO_3-N. This is comparable to studies elsewhere in semi-arid northwest China, where groundwaters unaffected by agriculture or industry have an average TDS of <300 mg/l and NO_3-N concentration of 7.3 mg/l (Guo and Wang 2004). Further down the groundwater flow line towards Jilantai, groundwater has evolved to become more alkaline and reducing, with cation exchange and halite dissolution being the prominent processes.

Present day

The present day groundwater system in Chahaertan has evolved significantly since irrigation started, and annual abstraction is now in the range 19–21 Mcm (Figure 14). There have been two major effects on the groundwater system: declining water levels and a marked decrease in water quality. This degradation has been exacerbated by engineering works to prevent virtually all seasonal over-bank flooding, which has greatly reduced wadi recharge. Groundwater levels have fallen by up to 0.5 m/yr for at least 20 years. Examining this decline in greater spatial detail with a dynamic balance groundwater flow model, using a factored sequence of the available groundwater abstraction, confirms that water level decline in the main Chahaertan irrigated area has decreased slightly since the 1990s. This has corresponded with the change of focus for groundwater development to Little

Chahaertan. However, if the decline continues at the same rate, production wells may start to show declining yields within 20 to 30 years, and the shallowest wells (100 m deep) are likely to have to be abandoned within 40 years.

The direct relationship between CFC concentrations and the degree of groundwater mineralisation (represented by TDS, Figure 11) clearly demonstrates that recycling of irrigation water is causing groundwater degradation, with a marked increase in salinity (a TDS increase from 400 mg/L up to 700-1900 mg/L) and an increase in nitrate concentrations (as N) from <5 mg/L up to 137 mg/L. The fact that re-infiltration of irrigation water has almost overtaken river infiltration as the main source of recharge in some areas has radically changed the chemistry of the local groundwater system. The majority of the wells within the irrigated area show elevated nitrate and salinity, as well as enrichment in Ca, Cl, SO_4 and Mg (Table ESM2, Figure 5). The generally slow movement of groundwater through the aquifer, which is supported by the modelling results, means there is a long lag time between cause and effect. It is likely that poor quality water from irrigation returns, which is moving downwards through the thick unsaturated zone (between 45 and 75 m thick in 2006), will continue to degrade groundwater quality in the aquifer for tens of years as it reaches the water table.

Conclusions

A combination of hydrodynamic and hydrogeochemical (including residence time) analysis and numerical groundwater modelling has provided a detailed insight into groundwater degradation in an irrigated area in semi-arid northern China, and by inference in other similar irrigated areas. An improved conceptual model of the groundwater system has revealed its complex nature and the multifold impacts of human activity.

Previous theories held that the main groundwater input at Chahaertan was subsurface flow from the southeastern boundary of the aquifer basin, recharged from runoff from the Helan Mountains. New evidence from this study shows that the main groundwater input in pre-development times was focussed river recharge in and around the now-irrigated area. Flood-prevention engineering works since development began have significantly reduced this recharge. Returns from inefficient flood irrigation have partially compensated (by volume) for the reduction in natural recharge, but abstraction nonetheless exceeds recharge, and groundwater levels continue to fall by up to 0.5 m/yr. Irrigation returns now comprise the largest proportion of local recharge.

The close relationship between the degree of groundwater mineralisation and the proportion of modern water, shown by CFC concentrations, clearly demonstrates that recycling of irrigation water is causing groundwater degradation.

Acknowledgements

This study was funded by the Australian Agency for International Development (AusAID), A$10 million, 2001-06, Alxa League Environmental Rehabilitation and Management Project (ALERMP). This paper is published with the permission of the Director, ALERMP and the Executive Director of the British Geological Survey (NERC).

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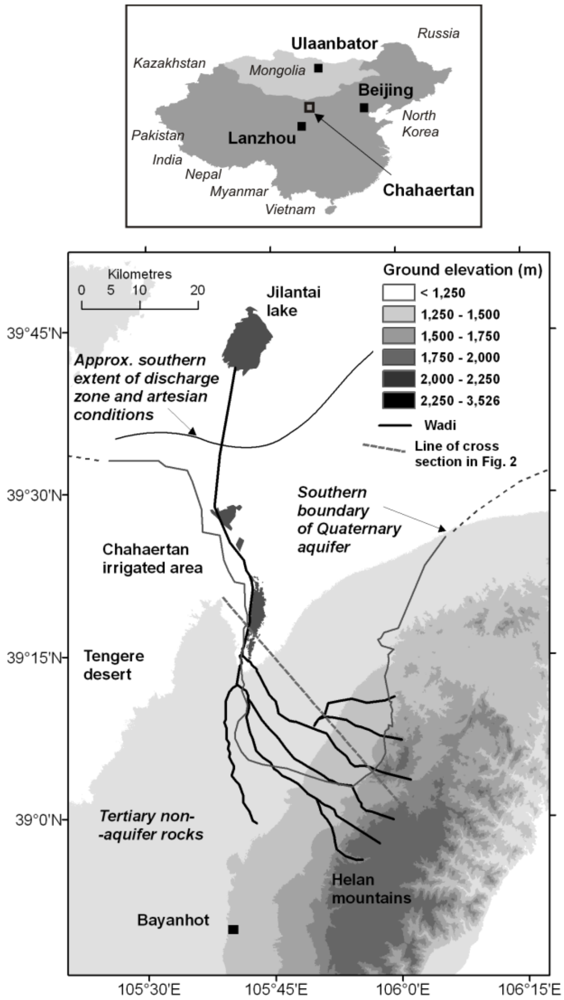

Figure 1 Location and generalised hydrology and hydrogeology of Chahaertan and the Quaternary aquifer.

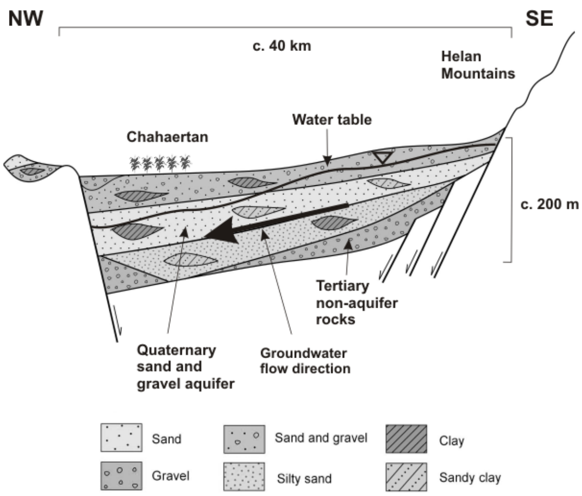

Figure 2 Schematic cross section of the Chahaertan Quaternary aquifer system along the line shown in Figure 1, and showing the approximate position of the groundwater table

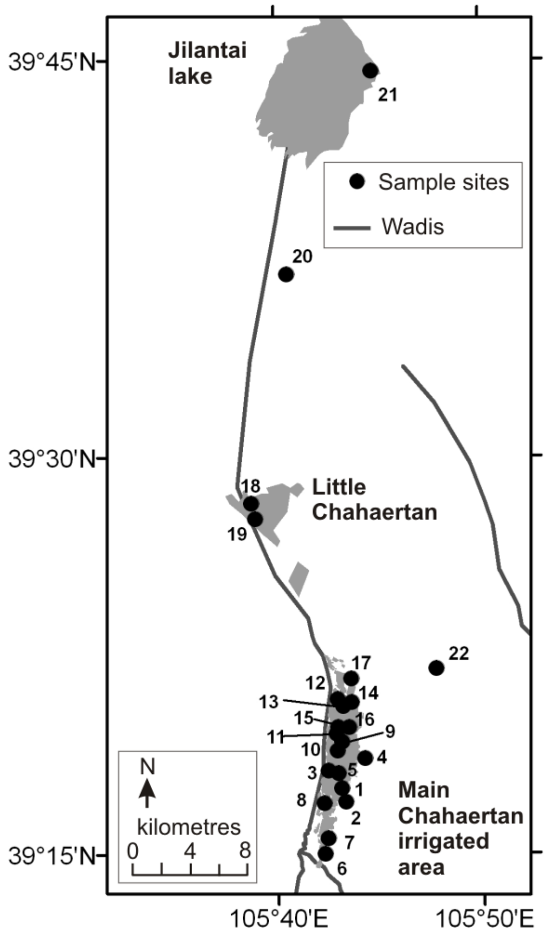

Figure 3 Location of groundwater chemistry sample sites at Chahaertan and the surrounding aquifer. Sample numbers are as in Tables ESM1 – ESM3

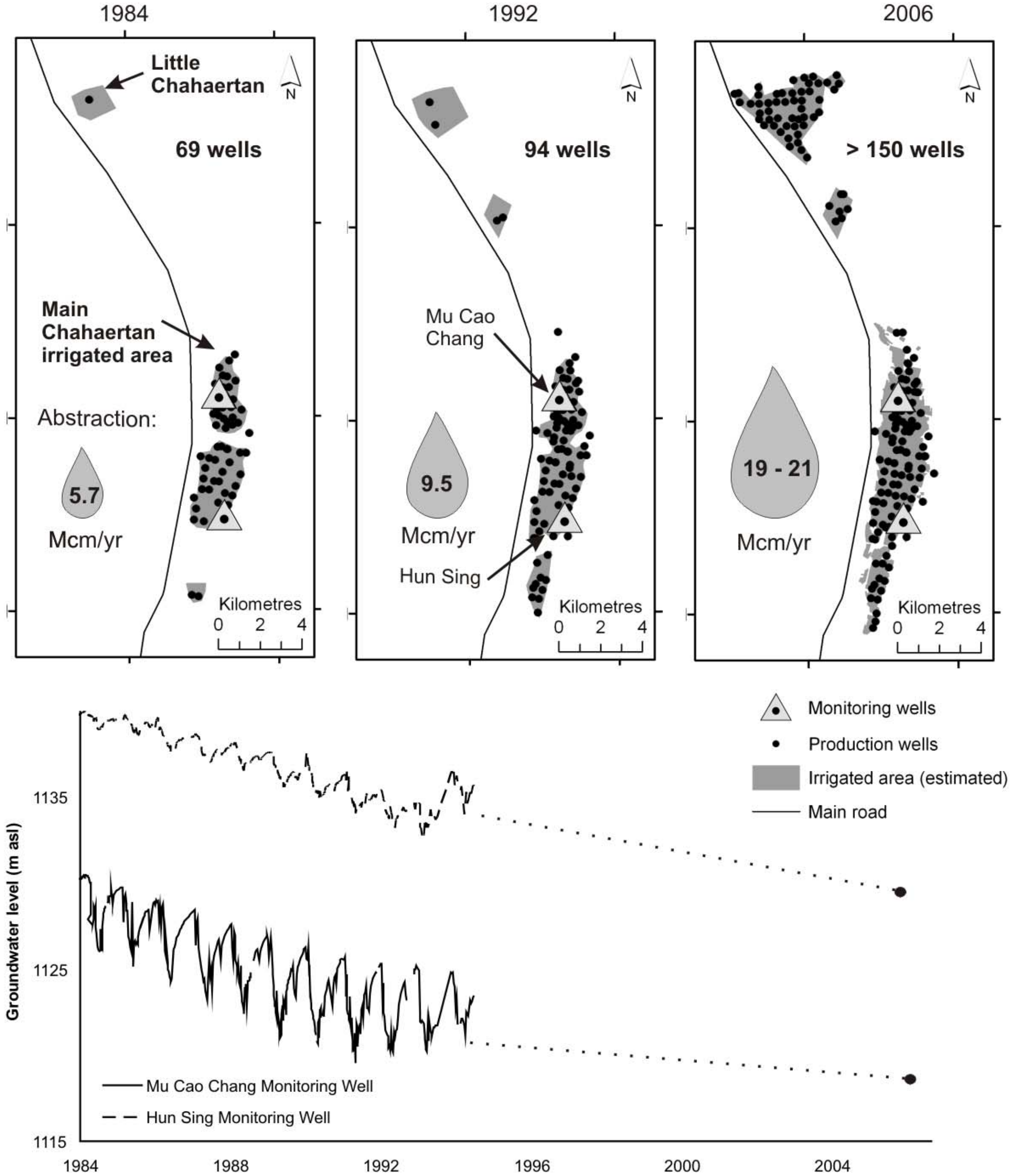

Figure 4 Schematic illustrating the increase in irrigated area, number of production wells and groundwater abstraction, and the simultaneous decline in groundwater levels at Chahaertan from 1984 to 2006.

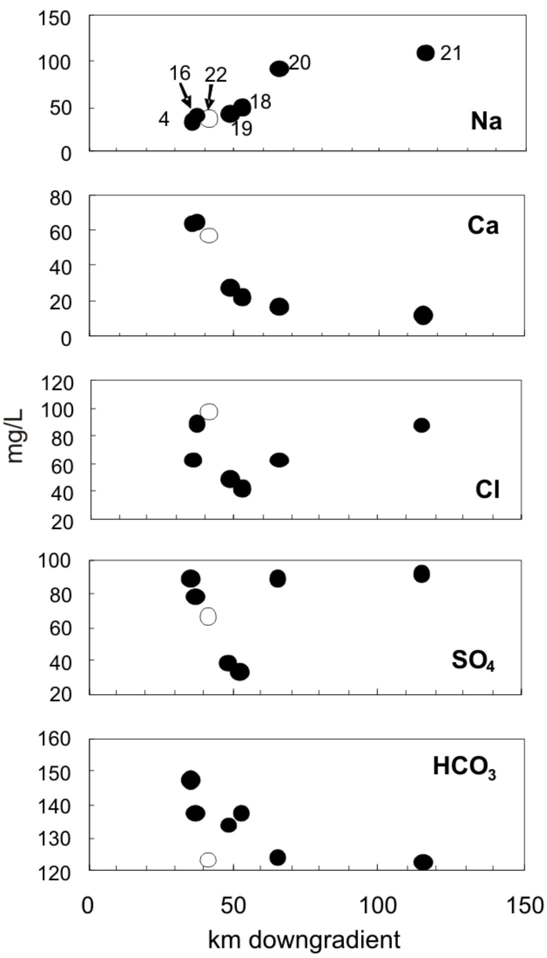

Figure 5 Major ion concentrations of pre-development Chahaertan groundwaters and groundwaters outside the irrigated area, plotted versus distance downgradient from the recharge area in the Helan Mountains. Site 22 lies off the assumed flowpath and is shown as an open circle. Sample location numbers are shown on the top (Na) plot.

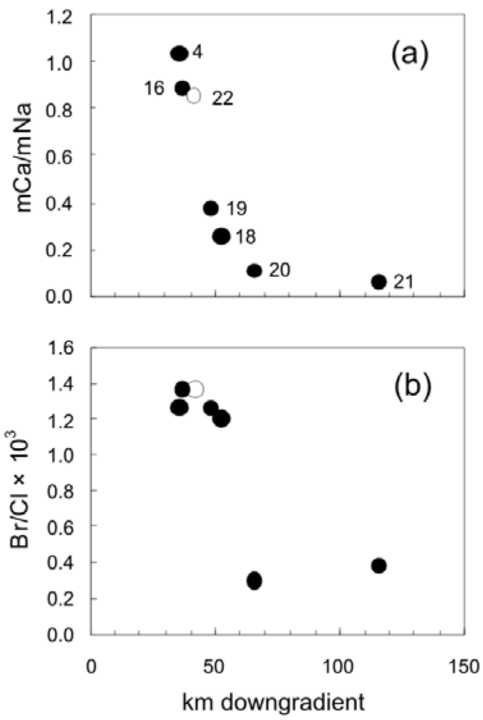

Figure 6 Plots of (a) Ca/Na molar ratios, and (b) Br/Cl ratios of baseline Chahaertan groundwaters and groundwaters outside the irrigated area, versus distance downgradient from the recharge area. Site 22 lies off the assumed flowpath and is shown as an open circle.

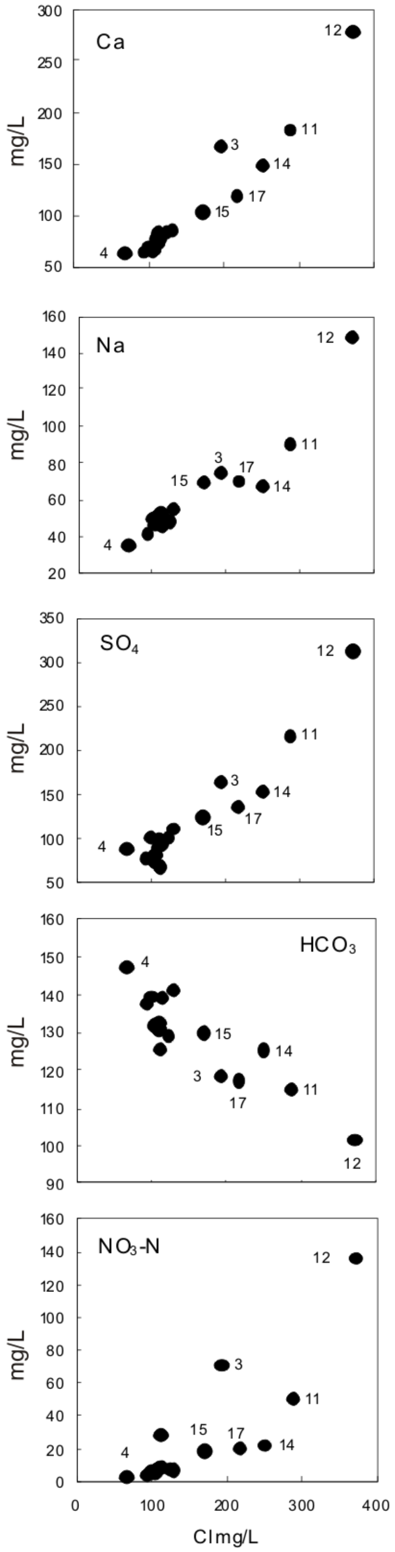

Figure 7 Plots versus Cl for the Ca, Na, SO_4, HCO_3 and NO_3-N contents of groundwaters from the irrigated area at Chahaertan. Selected site numbers shown.

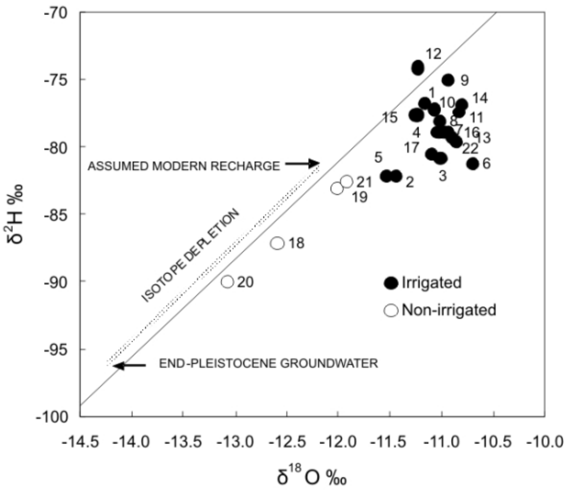

Figure 8 Plot of δ^2H versus δ^{18}O for all Chahaertan groundwaters within and outwith the irrigated area, with site numbers. The meteoric line (solid line) is for the nearest GNIP station at Yinchuan (longitude 106.13°E, latitude 38.29°N) (http://nds121.iaea.org/wiser/index.php) Yinchuan average isotope values are approximately –6.5 ‰ δ^{18}O and –45 ‰ δ^2H. The isotopic composition of end-Pleistocene groundwater is based on a 2‰ depletion in δ^{18}O, as found by Kreuzer et al. (2009) in the North China Plain.

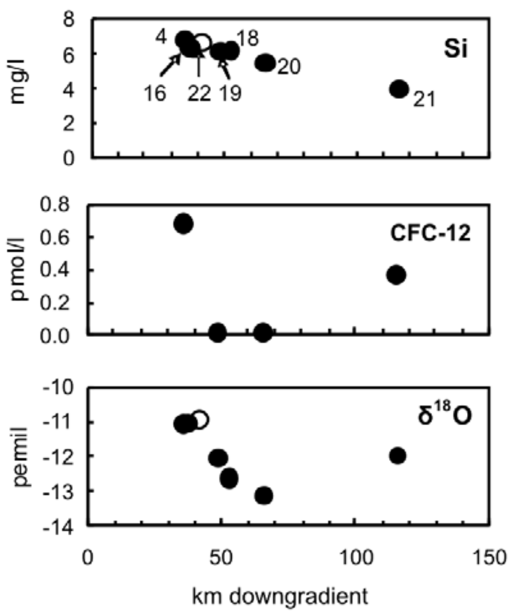

Figure 9 Plots of the Si, CFC-12 and δ^{18}O values for pre-development Chahaertan groundwaters and groundwaters outside the irrigated area, plotted versus distance downgradient from the recharge area. Site 22 lies off the assumed flowpath and is shown by an open circle.

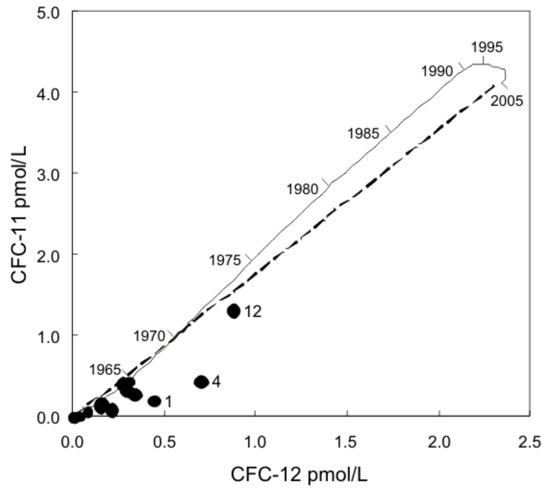

Figure 10 Plot of CFC-11 versus CFC-12 concentrations for Chahaertan groundwaters, with selected site numbers. The piston flow (solid) curve is based on secular changes in the Northern Hemisphere atmospheric mixing ratios over the past 50 years (data from http://water.usgs.gov/lab/software/air_curve/) and an average unsaturated zone recharge temperature of 15°C at an elevation of 1100 m ASL. The dashed mixing line is between modern and older CFC-free water.

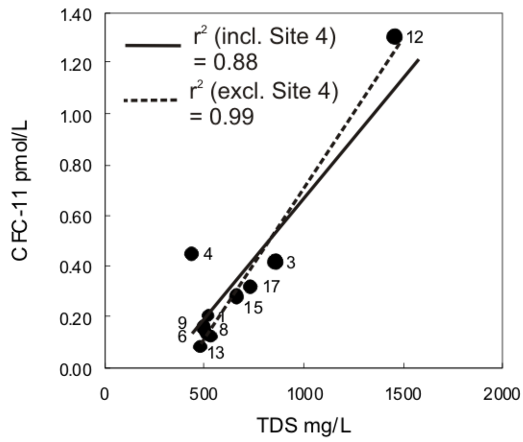

Figure 11 Plot of CFC-11 versus TDS (total dissolved solids) for Chahaertan groundwaters. Selected site numbers are shown.

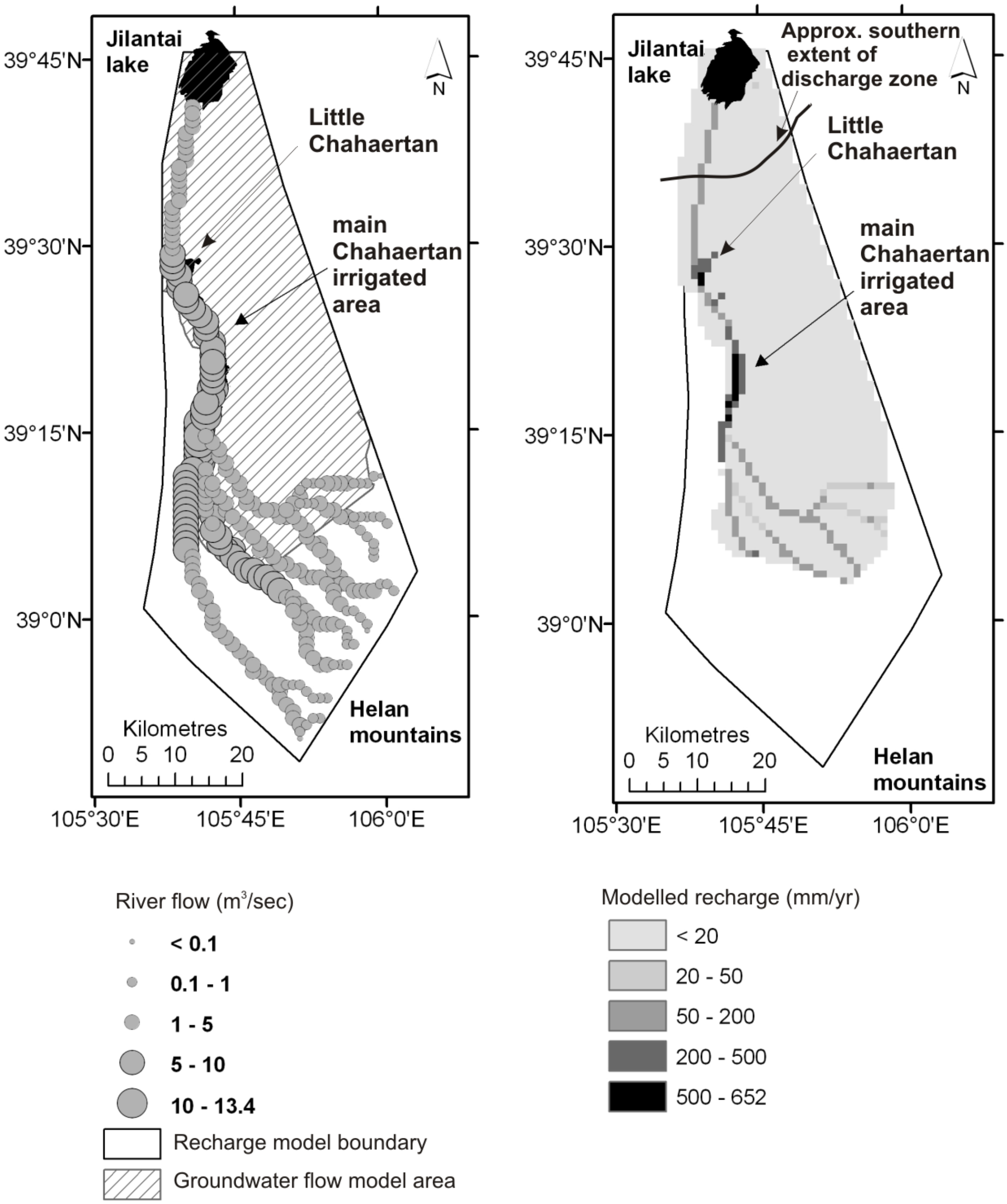

Figure 12 Simulated river flows for a large rainfall event (41 mm/day in the Helan Mountains) (left); and spatial distribution of modelled recharge across the Chahaertan aquifer (right)

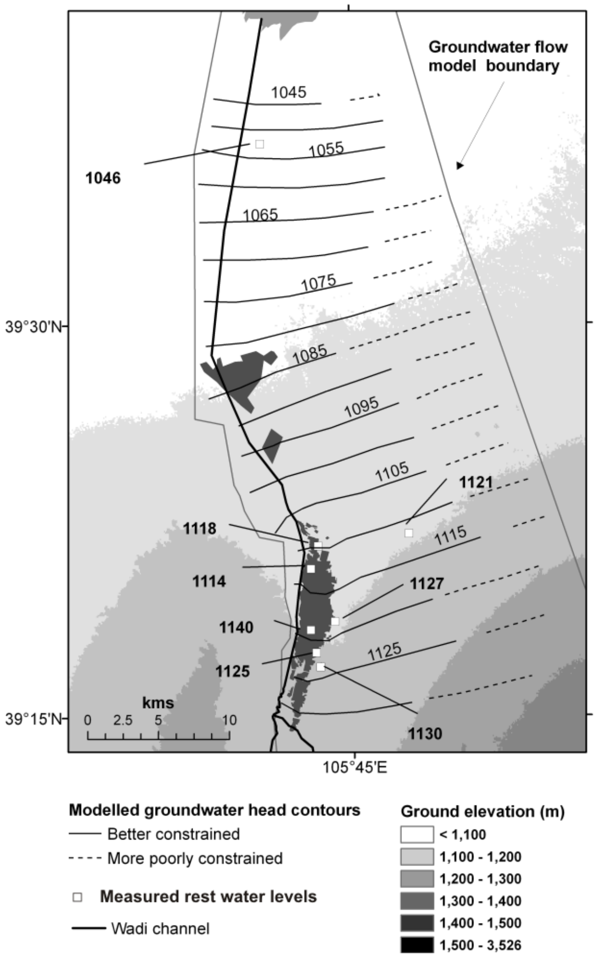

Figure 13 Modelled steady state groundwater head contours and available observed rest water levels in the aquifer around Chahaertan. All water levels in metres above sea level.

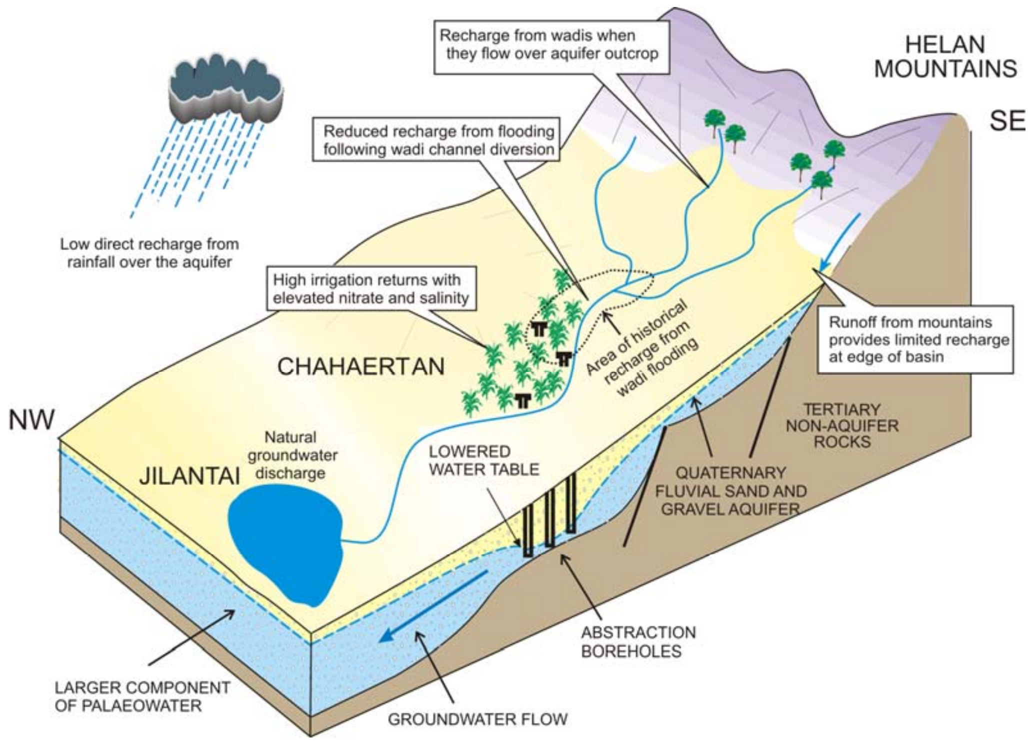

Figure 14 Conceptual model of post-development groundwater system at Chahaertan.

Table I Wadi channel characteristics

Wadi location	Channel width	Channel bed material	Annual flow events	Flow depth in channel	Roughness coefficient[1]
Helan Mountains	5 m	Coarse, high-energy gravel to boulder size deposits.	Unrecorded but likely to be 5-10 times, for >10 hours per event.	Average 0.5 m	0.05
Quaternary aquifer at Chahaertan	20–30 m	Fine sands and gravels.	3–4 times, for 3–10 hours per event. In smaller events, flow dies out c. 20 km north of Chahaertan.	Maximum 1 m, average 0.5 m	0.03
Quaternary aquifer at the lake at Jilantai	20–30 m	Fine sands.	2 times (maximum), for <5 hours per event.	Average 0.5 m	0.02

[1]Based on literature values for roughness coefficients for natural channels

Table II. Modelled recharge volumes at Chahaertan and across the Quaternary aquifer

Recharge source	Volume in Chahaertan local area (Mcm/a)	Volume across Quaternary aquifer (Mcm/a)
Rainfall	2	20
Wadi leakage	6	14
Irrigation returns	10	10
Total	**18**	**44**