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Groundwater degradation in the Chahaertan Oasis, Alxa League, Inner Mongolia

Groundwater Management Programme

Commissioned Report CR/06/220N

BRITISH GEOLOGICAL SURVEY

GROUNDWATER MANAGEMENT PROGRAMME

COMMISSIONED REPORT CR/06/220N

Groundwater degradation in the Chahaertan Oasis, Alxa League, Inner Mongolia

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Keywords

Inner Mongolia, China, groundwater resource, groundwater level, nitrate, groundwater degradation, groundwater management..

Front cover

Harvested corn and sunflower seeds at Chahaertan.

Bibliographical reference

Ó DOCHARTAIGH B É AND MACDONALD A M. 2006. Groundwater degradation in the Chahaertan Oasis, Alxa League, Inner Mongolia. *British Geological Survey Commissioned Report*, CR/06/220N. 69pp.

Keyworth, Nottingham British Geological Survey 2006

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Acknowledgements

A large number of individuals in the UK and China have contributed to the project. This assistance has been received at all stages of the study. In addition to the collection of data, many individuals have freely given their advice and assistance, and provided the local knowledge so important to the completion of this work. Of the many individuals who have contributed to the project we would particularly like to thank the following:

Shi Liang, Left Banner ALERMP Project Management Office, Bayanhot, Alxa League
Liu Dongmei, Left Banner Well Management Station, Bayanhot, Alxa League
Li Jinxiu, Left Banner ALERMP Project Management Office, Bayanhot, Alxa League
Niu Jianming, University of Inner Mongolia, Hohhot
Ellen Chin, AusAID, Bayanhot, Alxa League
Noel Haug, AusAID, Bayanhot, Alxa League
Adrian Williams, AusAID, Bayanhot, Alxa League
Andrew Hughes, BGS
George Darling, BGS
Daren Gooddy, BGS
Majdi Mansour, BGS
Chris Jackson, BGS
Chris Milne, BGS
Debbie Allen, BGS

The authors would also like to thank the farmers of Chahaertan, Alxa League for their generous assistance during this investigation.

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Summary

Chahaertan is an irrigated area entirely dependent on groundwater, in Alxa League, Inner Mongolia, China. It is known locally as the Chahaertan oasis. The oasis includes two distinct irrigated areas, Chahaertan and Little Chahaertan: in this summary, the name Chahaertan includes both these areas. Within the oasis there is intensive seasonal pumping of groundwater from more than 150 wells over an area of less than 30 km^2. Previous investigations at a nearby oasis, Yao Ba, revealed over-abstraction of groundwater and deteriorating groundwater quality (Adams and Shearer 1996). As a result of these findings, the sustainable management of agriculture in Chahaertan became one of the focuses of the Alxa League Environmental Rehabilitation and Management Project (ALERMP), which is funded by AusAID as part of their assistance to the Government of the People's Republic of China. As part of this project AusAID commissioned the British Geological Survey (BGS) to carry out an assessment of groundwater resource sustainability in Chahaertan, to establish procedures for groundwater management, and to provide relevant training to water resources staff in Alxa League.

During the groundwater investigation, the following work was carried out:

- A comprehensive chemistry survey, including the collection and analysis of new groundwater samples from 22 wells across Chahaertan and the surrounding area to provide baseline data on groundwater chemistry and residence times; and proposals for a long term groundwater quality monitoring regime.
- A survey of production wells, including accurately locating 168 wells and the collection and updating of information on annual abstraction; and a database of production well information was established with available data on all production wells, correlated to previous well inventories and electricity usage data.
- A survey of existing groundwater level monitoring wells and the measurement of groundwater levels; locating historical groundwater level data; establishing a database of historical and new groundwater level measurements; siting three new monitoring wells, which have subsequently been drilled; and proposals for a long term groundwater level monitoring regime.
- Collating existing data and information for Chahaertan and the surrounding aquifer, including maps, hydrogeological reports, geological logs, climatic data, and electricity usage records for production well pumps.
- Developing a numerical recharge and groundwater flow model using the model software ZOOM, to help establish a water balance, understand the groundwater system and forecast future trends.
- Training for counterpart staff, including on-the-job training in groundwater sampling, field chemistry analysis, groundwater level monitoring and groundwater data management; and a formal two day training course in groundwater resource investigation techniques.
- A report on the status of groundwater resources at Chahaertan, and recommendations for management strategies (this report).

The main results of the groundwater investigation are summarised here:

- The Chahaertan oasis lies on a Quaternary fluvial aquifer with a catchment area of about 1500 km^2, which varies in thickness from less than 30 m to more than 300 m.

Groundwater flows from south to north, and the main natural groundwater discharge from the aquifer is to Jilantai salt lake, some 35 km north of Chahaertan. Rainfall over the aquifer is low, less than 200 mm a^{-1}, but ephemeral rivers (wadis) flowing over the aquifer drain surface water from the Helan Mountains, where rainfall is more than 400 mm a^{-1}. Groundwater flow through the aquifer is slow: travel times from the southern edge of the aquifer to Chahaertan may be in excess of 5 000 years, and from Chahaertan to Jilantai, another 5 000 to 10 000 years.

- Interpretation of chemistry, stable isotope and CFC data combined with numerical modelling suggests that leakage from rivers and irrigation returns is the dominant aquifer recharge mechanism at the main Chahaertan irrigated area. Active recharge within the past 50 years has been detected, and much of the abstracted water may be only several hundreds of years old. This suggests that prior to development the Chahaertan area was a major recharge area – as periodic river flows spread out across the area and infiltrated to the aquifer. The diversion of rivers past Chahaertan may be reducing the current potential for recharge.
- North of the oasis towards Jilantai, there is little or no evidence of active recharge in the past 50 years. Groundwater from Little Chahaertan and Jilantai may have recharged during a wetter Holocene phase, or perhaps more likely, be the product of mixing between an old end-member (more than 10 000 years old) and younger water (perhaps several hundreds of years old). Overall recharge to the aquifer directly from rainfall is likely to be low (average 15 mm a^{-1}).
- Groundwater levels in the aquifer at Chahaertan have fallen by between 6 and 10 m in 20 years, and the available data indicates they are still falling at up to 0.5 m per year.
- Groundwater is moderately mineralised, with median total dissolved solids of 536 mg l^{-1} across the study area and an interquartile range of 459 to 695 mg l^{-1}. The pH is slightly alkaline (median of 7.67). All samples within the Chahaertan area are oxygenated – only samples from the north of the area, around Jilantai, are reducing. There is no evidence of arsenic or fluoride exceeding the WHO guideline values. Iron and manganese concentrations are also low across the aquifer. Major ion chemistry in the aquifer varies from Chahaertan to Little Chahaertan and Jilantai. Within Chahaertan, the cations are dominated by Ca and Mg and there is little variance in the Ca/Mg ratio. However, towards the discharge area at Jilantai, the dominant cation is Na, and the pH becomes more alkaline.
- Groundwater abstraction from Chahaertan is currently approximately 20 million cubic metres per year (Mm^3 a^{-1}). This is equivalent to approximately 50% of the recharge to the entire Quaternary aquifer, and may in time impact on flows to the Jilantai salt lake. Because the abstraction is focused in a small area, abstraction exceeds the local recharge in the Chahaertan area – natural recharge from river flow in the vicinity of Chahaertan is estimated at 10 Mm^3 a^{-1}.
- Detailed analysis of the chemistry data suggest that irrigation returns are seriously degrading the quality of the groundwater at Chahaertan. In wells with a high proportion of modern water (recharged since 1966) nitrate concentrations are highly elevated (20 to 130 mg l^{-1} NO_3 as N) and salinity is considerably higher than in groundwater dominated by older waters.

The indications are that the abstraction of groundwater from the Chahaertan oasis at current rates is unsustainable, and that agricultural practices in the oasis are leading to severe degradation of groundwater quality. If abstraction continues at current rates, water levels will continue to decline for tens of years at least, with individual wells starting to show declining yields within 20 to 30 years and the shallowest wells (100 m deep) possibly having to be abandoned within 40 years. If continued groundwater abstraction to support irrigated agriculture at Chahaertan is to be sustainable over a human timescale, the groundwater resource must be managed effectively.

The following recommendations are made for sustainable management of the groundwater resource at Chahaertan:

1. There should be no further abstraction wells drilled in Chahaertan. Current abstraction already exceeds local natural recharge.
2. Existing wells should reduce abstraction to halt the decline in groundwater levels and minimise returns from irrigation. This is likely to require reducing abstraction by up to 30%.
3. Fertiliser and pesticide use should be controlled. With some wells showing nitrate concentrations in excess of 130 mg l^{-1} NO_3 as N, the indications are that excess fertiliser is being used and is being leached to the aquifer. As well as a reduction in the volume of irrigation water, there should be a reduction in the amount of nitrogen fertiliser used, in order to minimise nitrate leaching.
4. Consideration could be given to increasing recharge from river flow to the south of Chahaertan by constructing a recharge lagoon. This would simulate the natural predevelopment system, when the aquifer may have received considerably more recharge from river leakage. The feasibility and cost-effectiveness of this approach, however, would need to be examined in more detail.
5. The catchment must be treated and managed as a whole. The impact of abstraction and any modifications to river channels will have an effect on the Jilantai salt lake and corresponding salt works. Therefore, the impact of any measures taken in Chahaertan on the catchment as a whole must be taken into consideration.

To effectively manage the aquifer at Chahaertan it is essential to monitor the groundwater system. Only with this information will it be possible to test whether the management options are working. Water levels in the nine monitoring boreholes in Chahaertan should be measured every month to assess the decline in water levels across the aquifer. Nitrate concentrations and SEC should be monitored in 10 pumping boreholes at least three times per year. Monitoring data must be stored, reviewed and communicated to all relevant institutions. To help build confidence in any future time-variant groundwater model, data on daily rainfall data and river flows across the aquifer must be collected.

1 Introduction

1.1 BACKGROUND

This report describes the results of an investigation of the groundwater resources in the irrigated oasis of Chahaertan. Chahaertan is in Left Banner, Alxa League in the Inner Mongolia Autonomous Region of the People's Republic of China. The investigation was carried out as part of the Alxa League Environmental Rehabilitation and Management Project (ALERMP), which is funded by AusAID as part of their assistance to the Government of the People's Republic of China.

The ALERMP worked towards improved sustainable resource use and poverty reduction in Alxa League of the Inner Mongolia Autonomous Region for five years, between June 2001 and June 2006. During an extension to the project, running from July 2006 to January 2007, one of the main focuses was on the sustainable management of agriculture in the Chahaertan oasis. This oasis is entirely dependent on groundwater for its existence. The sustainability of groundwater resources in Chahaertan had been identified as an issue following previous investigations at a nearby oasis, Yao Ba, which revealed over-abstraction of groundwater and deteriorating groundwater quality (Adams and Shearer 1996). As part of the project extension AusAID commissioned the British Geological Survey (BGS) to carry out an assessment of the groundwater resource sustainability in Chahaertan, as well as to establish procedures for groundwater management, and to provide relevant training to water resources staff in Alxa League.

1.2 CHAHAERTAN OASIS

Chahaertan and Little Chahaertan are irrigated areas in Xilingaole Sumu (now incorporated in Jilantai Township) in Left Banner, Alxa League, in the western part of the Inner Mongolia Autonomous Region of the People's Republic of China (Figure 1). The two oases lie approximately 50 km north of Bayanhot, the administrative capital of Alxa League, between longitude 105° 37' to 105° 45' east and latitude 39° 14' to 39° 29' north (Figure 1).

The oases comprise a group of villages, or gachas, which are reliant on irrigated agriculture to produce cash and subsistence crops, and livestock fodder. Little Chahaertan is a separate, smaller oasis some 10 km to the north of Chahaertan (Figure 1).

- The irrigated area in Chahaertan is 17.7 km^2 and in Little Chahaertan is some 10 km^2.
- The total population of the Chahaertan oases is about 6000, most of which are involved in irrigated agriculture. A minority are herders, but herding activities have been restricted from 2004 to 2006 as a series of grazing bans were implemented in the area.
- The dominant crop types in the Chahaertan oases are maize, wheat, watermelon, sunflower and peppers. Alxa League is a semi-arid area and irrigation, using groundwater from wells located within the oases, is essential for crop production.

Previous studies have looked at aspects of groundwater resources in Chahaertan and in the surrounding area (e.g. Groundwater Development and Utilisation Teaching and Research Office, 1984; Yan and Wu, 1996). Surveys of production wells in the oases were carried out in 1992 and 2002 (e.g. Left Banner Water Management and Water Resource Office 1992). Aspects of the hydrogeology of the area are also described in reports accompanying hydrogeological maps of the area (People's Liberation Army, 1976 and 1980).

The only detailed report on the groundwater resource at Chahaertan dates from 1984 (Groundwater Development and Utilisation Teaching and Research Office, 1984). Since this time there has been no systematic review or assessment of the groundwater resource and the impact of abstraction and agriculture. The results of a 1990s investigation into groundwater resources at another oasis in Alxa League, Yaoba, some 200 km to the south of Chahaertan, indicated that groundwater in Yao Ba was being overabstracted and that groundwater quality was deteriorating (Adams and Shearer 1996). Based on this study, restrictions were placed on the further expansion of irrigated land and drilling of new production wells in existing oases across Alxa League, including Chahaertan. However, there has been little or no recent groundwater investigation at Chahaertan, and therefore little on which to base management strategies.

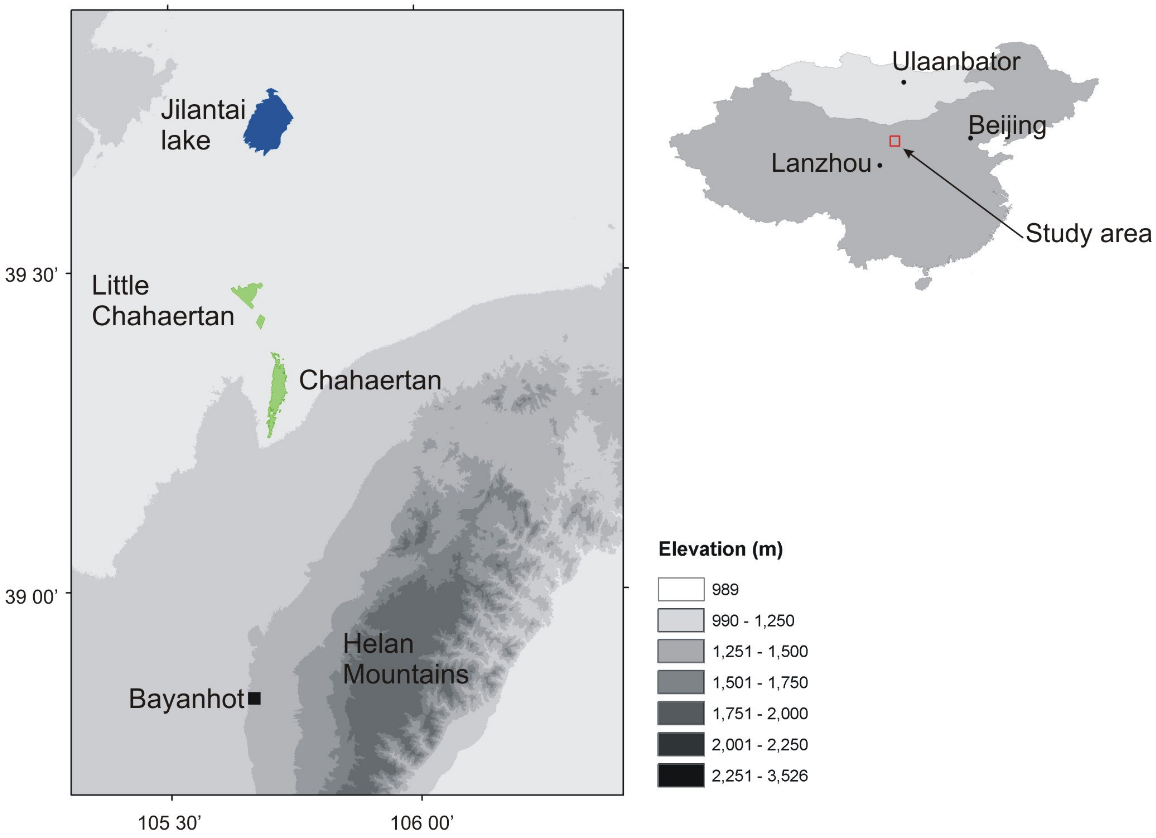


Figure 1 Location of Chahaertan and Little Chahaertan

1.3 GROUNDWATER DEVELOPMENT IN CHAHAERTAN

The earliest available record of a groundwater abstraction well at Chahaertan was in 1968. By 1984, there were some 69 production wells in operation, an irrigated area of 15 000 mu (approximately 10 km^2) and a total abstraction of 5.7 million cubic metres per year (Mm^3 a^{-1}) (Groundwater Development and Utilisation Teaching and Research Office 1984). These figures relate only to Chahaertan: groundwater abstraction was occurring at Little Chahaertan in 1984, but there is no available information for this time.

By 1984, groundwater levels in Chahaertan had been falling by between 0.2 and 0.75 m a^{-1} (Groundwater Development and Utilisation Teaching and Research Office 1984). The groundwater development report stated that the total allowable water level decline in the Chahaertan area was 7 m, and accordingly set a design period for the oasis of 20 years, with a maximum groundwater abstraction rate of 5.5 $Mm^3\ a^{-1}$. However, as described above, even at the time of the report, in 1984, this abstraction rate had already been exceeded.

Most of the expansion in the Chahaertan oasis occurred by 1992, at which time there were some 94 production wells and an irrigated area similar to today, with an estimated abstraction of 9.5 $Mm^3\ a^{-1}$ (Left Banner Water Management and Water Resource Office 1992)

The current investigation (see Section 4) has shown that there are currently 168 production wells in the Chahaertan oases: 119 in Chahaertan and 49 in Little Chahaertan. The total number of wells currently in operation is uncertain, but it is likely that approximately 110 wells in Chahaertan and over 40 wells in Little Chahaertan are in use every year. Total abstraction from the oases is estimated at 18.5 to 21 $Mm^3\ a^{-1}$ (Section 4.6.2). Abstraction is dominantly for irrigation, with a small proportion used for drinking water for both humans and livestock.

A diagram illustrating the development of groundwater abstraction and irrigated areas in the Chahaertan oasis is presented in Figure 2.

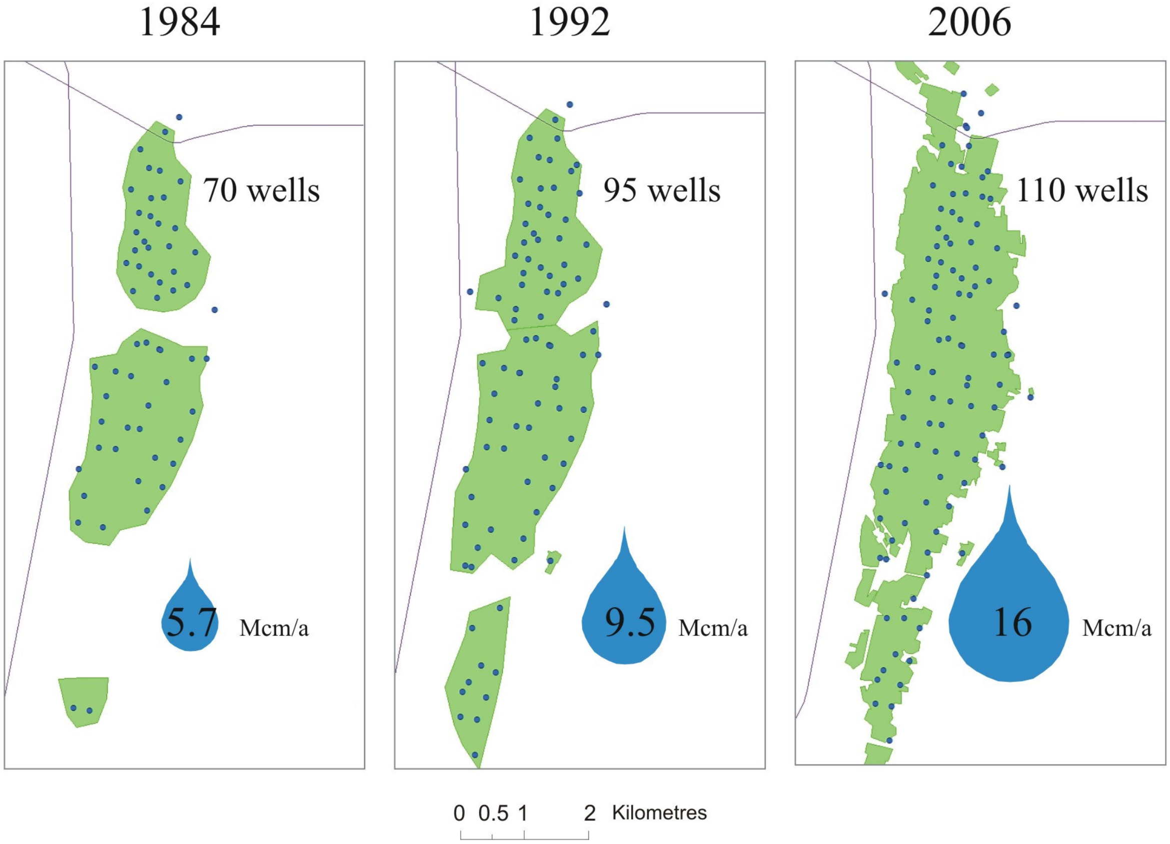


Figure 2 Diagram illustrating the development of groundwater abstraction and irrigated areas in the Chahaertan oasis between 1984 and 2006 (Mcm/a is million cubic metres per year).

1.4 AIMS AND PROGRAMME OF WORK

The aims of the ALERMP groundwater investigation were:

- To review groundwater development in the Chahaertan oases and to design and assist in the implementation of a water resources monitoring programme for the irrigated area with relevant water resources staff in Left Banner.

- To establish a set of procedures to manage well information, and to survey well locations with a GPS to identify number, type and locations.
- To establish an appropriate numerical groundwater model for Chahaertan and to train relevant staff in the design and operation of the model.
- To provide additional advice and training in groundwater management.

To achieve these aims the following programme of work was carried out:

- Collating existing information on groundwater in the Chahaertan oases and the surrounding aquifer.
- Collecting water samples from 22 production wells for chemical analysis to provide baseline data on groundwater chemistry and residence times.
- Organising a survey of all production wells (more than 150 wells) in the oases, and designing a system for managing well information.
- Developing a numerical groundwater model using the software ZOOM.
- Designing a long term monitoring programme for groundwater levels and groundwater quality.
- Providing on the job training in groundwater sampling, field chemistry analysis, groundwater level monitoring and groundwater data management to appropriate staff, and providing a formal two day training course in groundwater resource investigation to appropriate staff.
- Writing a report on the sustainability of groundwater resources in the Chahaertan oases, including recommendations for groundwater monitoring and management.

2 Data sources

Relevant groundwater data were obtained from maps, reports, field data collection, laboratory analysis and discussions with relevant stakeholders. Many of the reports are detailed in the reference list of this report. All of the data sources consulted are also listed in Appendix 1, with accompanying notes where relevant.

There have been a number of previous hydrogeological studies in Alxa League that have included the aquifer from which the Chahaertan wells abstract (People's Liberation Army, 1976 and 1980; Groundwater Development and Utilisation Teaching and Research Office, 1984; Yan and Wu, 1996). Reports of these studies provide basic and in some cases detailed information on the wider aquifer, including aquifer geology, geometry, hydraulic properties, aquifer flows, climate, and historical groundwater abstraction, well yields, groundwater levels and groundwater chemistry. This information provided an essential basis for the current assessment of groundwater resources at the Chahaertan oases.

Also of direct relevance were two previous surveys of production wells in the Chahaertan oases, carried out in 1992 and 2002, which provided information to help establish the historical development of the oases.

Maps of the Chahaertan and wider aquifer areas – both topographical and geological – were not readily available. Locating the required maps took considerable time. The efforts of the GIS expert on the project were invaluable for digitising (scanning and georeferencing) the required maps so that they could be used in a GIS environment. This not only made data interpretation more efficient and effective, but in some cases (where the paper map was not available for purchase) was the only way to ensure that a permanent version of the map was available to the project.

3 Setting

3.1 TOPOGRAPHY

The Chahaertan oases lie at between 1100 and 1200 m elevation on a plain to the northwest of the Helan Mountains, approximately 23 km from the foothills of the mountains at the closest point (Figure 1). The Helan Mountains reach over 3000 m elevation at their highest point. They extend for over 150 km from southwest to northeast, but are only approximately 40 km wide. The foothills of the Helan Mountains on their northwestern side lie at approximately 1500 m elevation, and from here the land slopes towards the north and northwest at a gentle angle of less than 1.3%. To the west is the Tengere desert, which generally lies at more than 1200 m elevation. The lowest point in the area lies to the north of Chahaertan at Jilantai, at approximately 1000 m elevation.

3.2 CLIMATE

The climate in the study area is semi arid to arid. Rainfall is highest over the Helan Mountains (approximately 410 mm a^{-1}) and lowest at Jilantai (approximately 110 mm a^{-1}), and varies significantly from year to year (Figure 3). Most rainfall occurs between June and September as short lived, intense events (Appendix 2). Most precipitation falls as rain, with a small amount of snowfall in winter. Daily rainfall measurements are made at Bayanhot and Jilantai, but were only available for short periods between 2003 and 2005, and a complete year of measured daily data was not available. A limited dataset of daily rainfall for Chahaertan for summer 2006 was also available (Appendix 2). The data indicate that most days are rain free, but that rainfall events of more than 25 mm d^{-1} can occur in Jilantai. Using these datasets, combined with the long term average monthly rainfall, synthetic rainfall series were created for Jilantai, Bayanhot and the Helan Mountains. This process is discussed in detail in Appendix 4 when the development of the groundwater model is described.

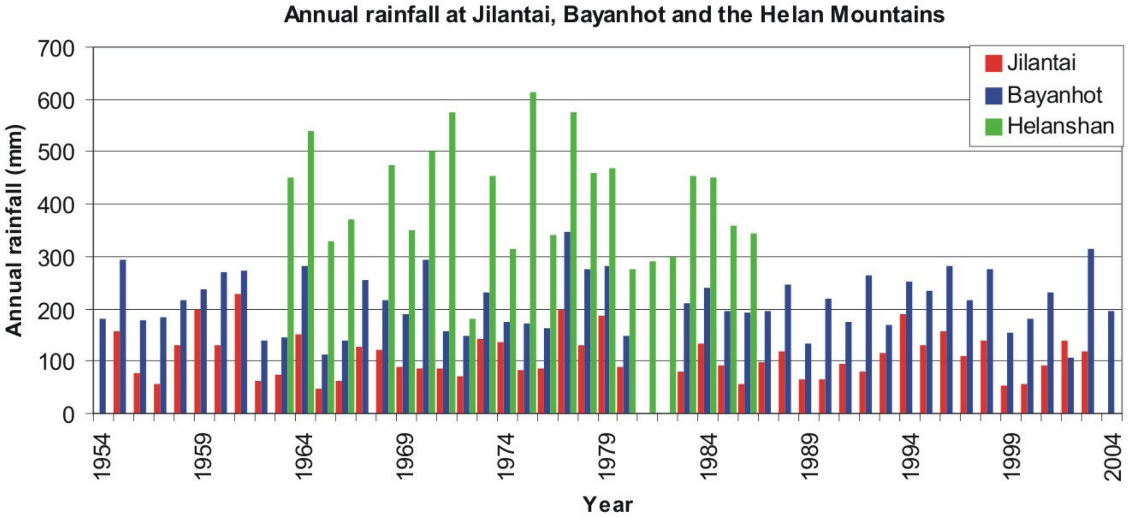


Figure 3 Annual rainfall for the Helan Mountains, Jilantai and Bayanhot. Rainfall at Chahaertan is similar to Bayanhot (Appendix 2) (Alxa Meteorological Office; Yan and Wu, 1996; ALERMP data).

Potential evapotranspiration is significantly higher than rainfall. It is highest at Jilantai (3000 mm a^{-1}) and lowest in the Helan Mountains (1400 to 1700 mm a^{-1}) (Figure 4), and everywhere is highest between May and August (Appendix 2). Evapotranspiration in Chahaertan exceeds 8 mm d^{-1} in June and July (Jerie 2006) (Appendix 2).

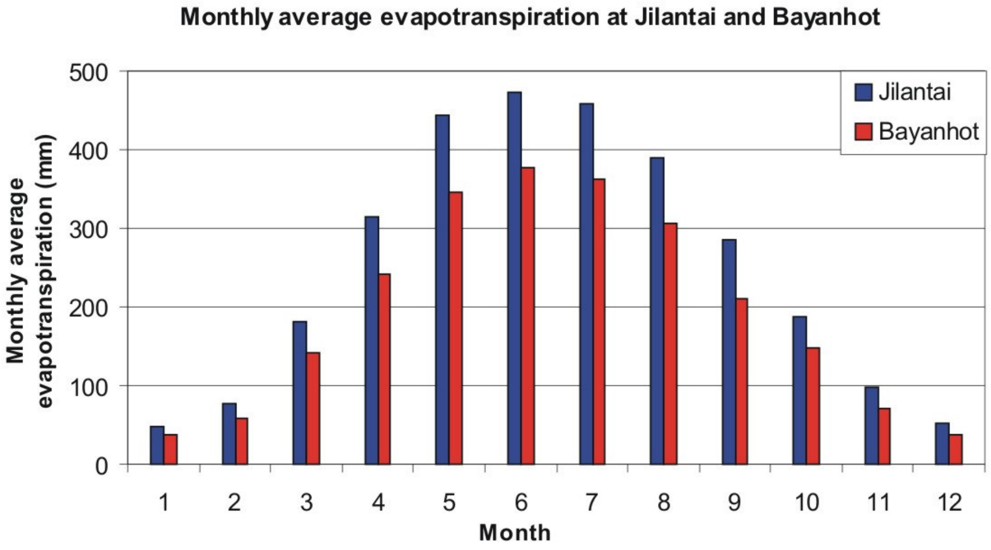


Figure 4 Monthly average evapotranspiration at Jilantai and Bayanhot (Alxa Meteorological Data). Evapotranspiration at Chahaertan is generally between these two.

3.3 SURFACE WATER DRAINAGE

There is no permanent surface water drainage in the study area. Surface water drainage is dominated by ephemeral river beds (wadis) that flow from the Helan Mountains towards the salt lake at Jilantai, which forms the discharge point in this internal drainage system (Figure 5). Higher rainfall and lower evapotranspiration in the mountains, combined with steep slopes, mean that most river flow is derived from the mountains, with runoff to rivers from the Quaternary aquifer comprising only a small proportion of river flow (see Appendix 4).

Two main river systems flow over the aquifer (Figure 5). The easternmost system is smaller, with just one river channel that disappears before it reaches Jilantai lake. The larger system comprises at least four tributary channels that merge to the south of Chahaertan to form one main channel. Before the development of the Chahaertan oasis, this main channel flowed through the middle of what is now Chahaertan oasis, and probably led to the development of the slightly loamier soils that now exist in the oasis (Section 4.6). It has since been channelled away from the centre of the oasis and now flows past the south and west sides of the irrigated area (Figure 5).

In the Helan Mountains, the river channels are typically 5 m wide with coarse fluvial deposits that indicate large and high energy river flows (Figure 6). Over the Quaternary aquifer, the river channels are typically 20 to 30 m wide. At Chahaertan, the main channel is often quite deeply incised below the surrounding land, but the tributary channels to the south are normally shallower (Figure 6). In the Chahaertan area, the river channel has been engineered to minimise flood risks, with embankments and reinforced river banks along many stretches.

River flows are not monitored anywhere in the study area, but field observations and anecdotal information from staff at the Comprehensive Extension Station and from farmers at Chahaertan has been used to build up an impression of river flow characteristics.

The river at Chahaertan flows three to four times each year. Flow in the river only reaches as far as the lake at Jilantai once or twice each year, during the largest rainfall events. During these events, the river at Chahaertan flows for up to 10 hours, to a maximum depth of 1 m. During slightly smaller rainfall events, the river at Chahaertan flows for 3 to 4 hours, and flow dies out about 20 km north of Chahaertan, halfway between the oasis and Jilantai lake. During most rainfall events, the river at Chahaertan does not flow at all. In the absence of river flow monitoring data, an estimate of river flows was made using the widely used Manning equation for open channel flow. Assuming an average flow depth of 0.5 m in the main channel at Chahaertan, the calculated river flow is between 20 and 30 m^3 sec^{-1}, depending on the roughness coefficient selected.

The fact that flow in the rivers usually dies out before it reaches Jilantai indicates that infiltration of river water to the underlying aquifer is an important process (see Section 4.3).

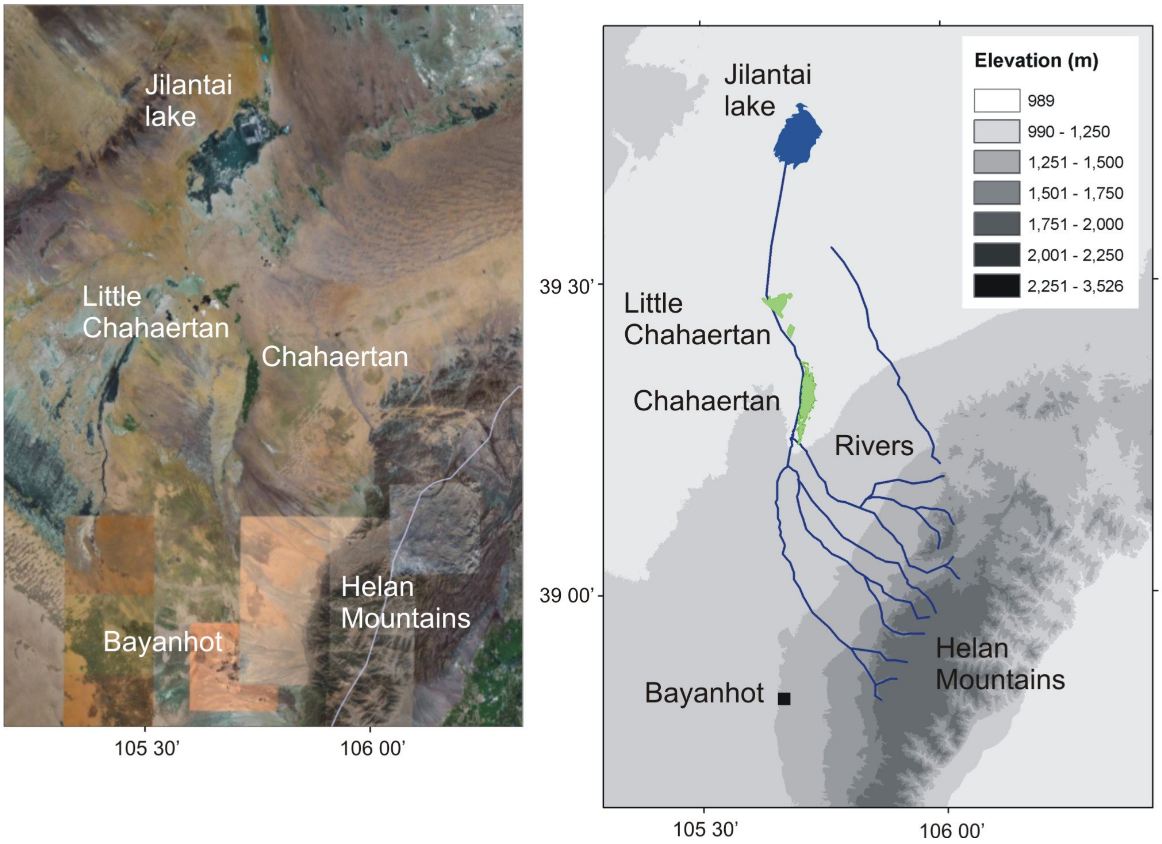
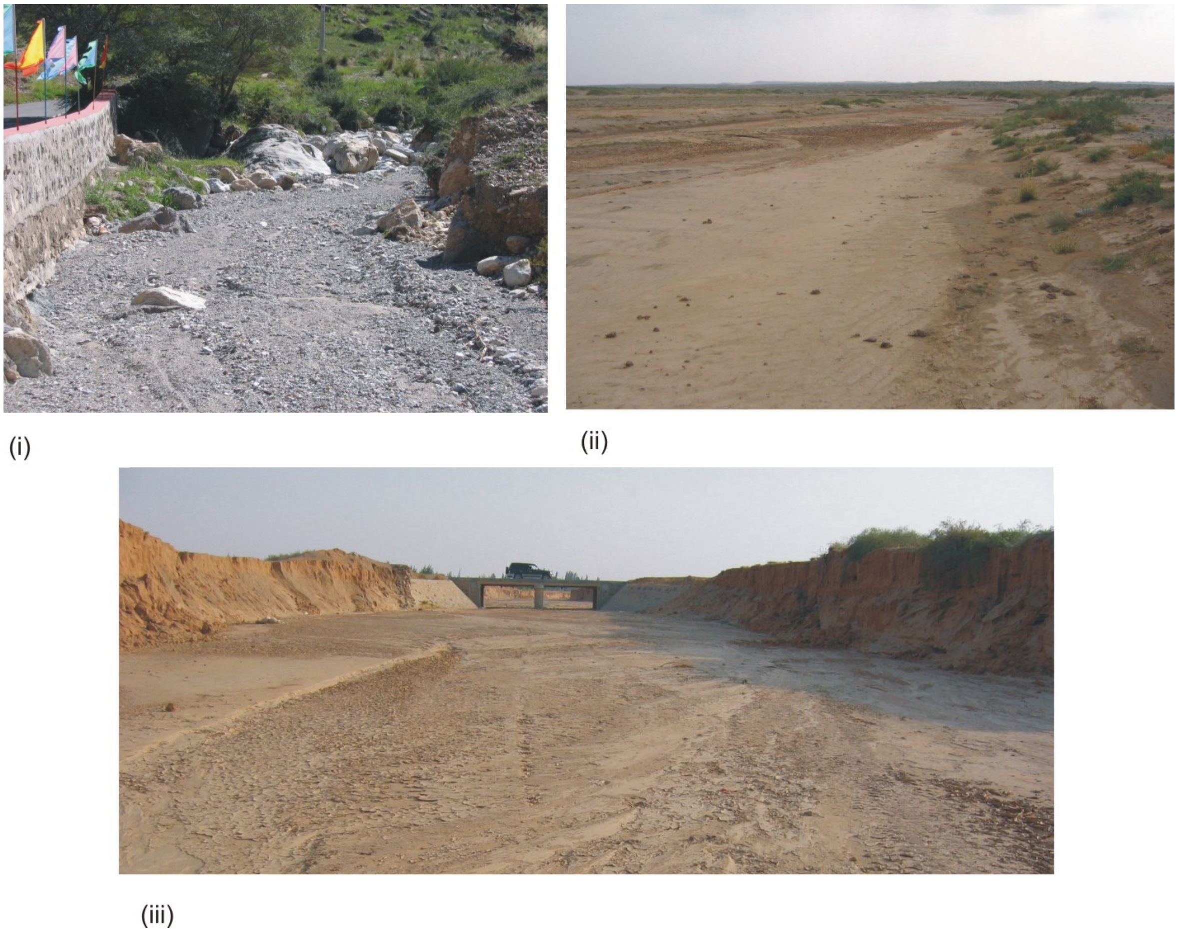


Figure 5 Satellite imagery (left) and map (right) of the study area, showing the Chahaertan oases and ephemeral river beds that run from the Helan Mountains in the southeast to Jilantai lake in the north. Note that there is no evidence from satellite imagery that the eastern-most river reaches Jilantai. (Satellite imagery from Google Earth).



(i)

(ii)

(iii)

Figure 6 Dry river beds. (i) In Helan Mountains, where coarse grained deposits, including boulders, indicate large, high energy river flows. (ii) Tributary channel south of Chahaertan where the channel is not incised. (iii) Main channel next to Chahaertan where the channel is deeply incised.

3.4 GEOLOGY

The geology of the aquifer was interpreted from hydrogeological maps and reports and from geological logs. Geological logs for 49 wells in Chahaertan were made available. A simplified geological map of the study area is shown in Figure 7.

The aquifer beneath Chahaertan and the surrounding area consists of Quaternary sediments, dominantly fluvial, which were laid down in a faulted basin. The aquifer is underlain and bounded to the west, south and north by low permeability Tertiary and older sedimentary rocks that are effectively non-aquifers. The maximum thickness of this Quaternary aquifer is thought to be in the Chahaertan area and to be more than 200 m (People's Liberation Army, 1980).

The faults that bound the aquifer to the west, south and east are shown in Figure 7. A major fault system called the Helanshan or Haidan fault forms the eastern aquifer boundary, separating the aquifer from the Tertiary sandstones, conglomerates and limestones of the Helan Mountains. This system consists of several associated parallel faults that run from southwest to northeast and dip at between 60 and 80° towards the west. The western aquifer boundary is formed by the Bayanhot fault, which runs from south to north and dips to the east at approximately 60°. It separates the aquifer from Tertiary sandstones to the west, which lie at a slightly higher elevation than the plain formed by the Quaternary aquifer, and are locally termed the Tableland (Yan and Wu 1996). The southern aquifer boundary is formed by a separate fault that runs from east to west joining the Helanshan and Bayanhot faults, and separates the aquifer from Tertiary sandstones to the south (Yan and Wu 1996).

Movement on these faults during the late Tertiary or early Quaternary created a basin that varied in depth from less than 30 m near the Helan Mountains to more than 200 m around Chahaertan. The basin was infilled mainly by sediments eroded from the Helan Mountains and carried down into the basin by high energy rivers. These sediments – mainly sand, gravel and silt – form the Quaternary aquifer which exists today (Yan and Wu 1996). Some sediment, mainly in the west of the aquifer basin near the Bayanhot fault, was eroded from the Tableland to the west and also carried into the basin by rivers.

The Quaternary aquifer therefore comprises mainly fluvial deposits, which on a broad scale grade from coarser-grained nearer to the mountains, to finer-grained further from the mountains. There are also minor aeolian and lacustrine (lake) deposits. The deposits vary significantly over small areas and with depth, as shown by the available geological logs from wells in Chahaertan. Most of the sequence consists of fine to coarse grained sand and gravel, but there are also thin beds of silt and clay at different depths, some of which may be lacustrine deposits. The silt and clay beds typically do not extend over large areas, and do not form persistent layers across the aquifer. Some beds of coarse gravel occur, mainly at depth in the aquifer and near the aquifer boundary faults, close to the sediment source.

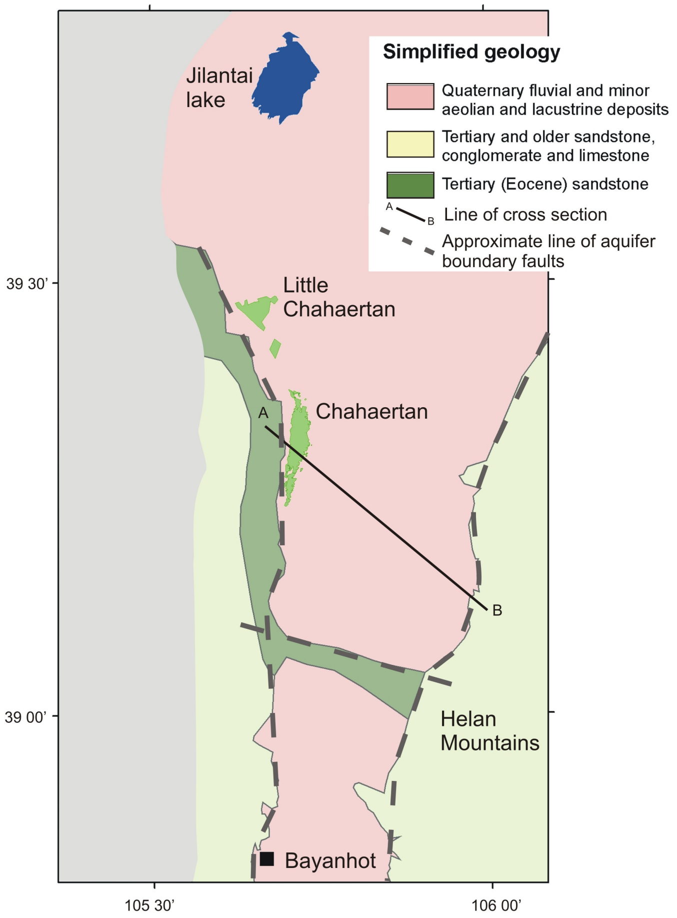
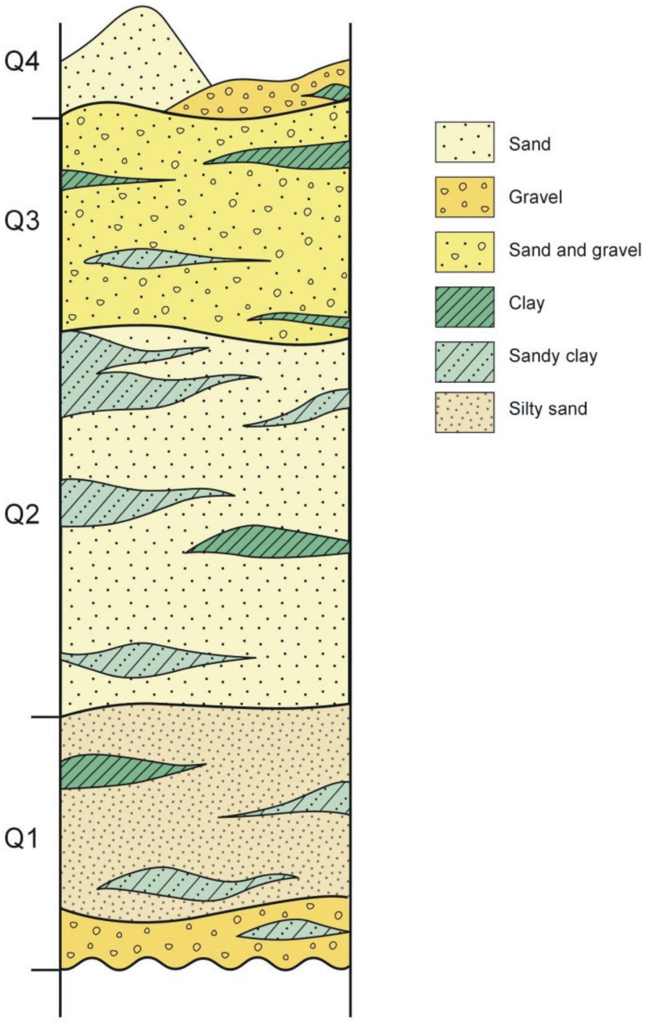


Figure 7 Simplified geological map showing the extent of the Quaternary deposits. Grey shading indicates outside the study area.

The main lithological features of the Quaternary sequence are illustrated in Figure 8, and a schematic cross section of the geology across the aquifer is shown in Figure 9. Photographs showing examples of the Quaternary sediments are presented in Figure 10.

3.5 SOILS

The only information on soil types in the study area is from a previous ALERMP study which looked at fields in one area of Chahaertan (Jerie 2006). Here, the soils were generally free draining with no indication of water perching in any soil layer down to 1.8 m, and comprised largely a uniform silty loam with small proportions of clay and fine sand (generally less than 10%). All the soil profiles investigated also had at least one layer of fine to medium-grained sand.



Q_4	Q_4^{eol} – aeolian deposits, largely light yellow, fine to medium grained, blown sand. Q_4^{pl} – mostly found west of Chahaertan near river, comprising gravel, pebbles and some clay.
Q_3	Fluvial and lacustrine deposits. Gravel, sandy-gravel and coarse to fine sand, with some very thin clay layers
Q_2	Q_2^{l} – sandy clay, fine-medium sand; in some areas coarse sand. An impersistant calcrete layer between this and Q_2^{pl}. Q_2^{pl} – green-yellow or pale yellow, clay-sand, sand-gravel. Increases in thickness from SE to NW.
Q_1	Q_1^{l} – 10 – 20 m thick, orange-yellow or green-yellow, silty sand with some sandy clay. Q_1^{pl} – Lowest unit is largely gravel with clayey sandy, 7.2 – 7.9 m thick. Upper parts are sand or sandy clay. Grain size becomes finer from east to west.

Figure 8 Schematic representation of the Quaternary sedimentary sequence in the Chahaertan area and wider aquifer, based on information from reports and geological logs.

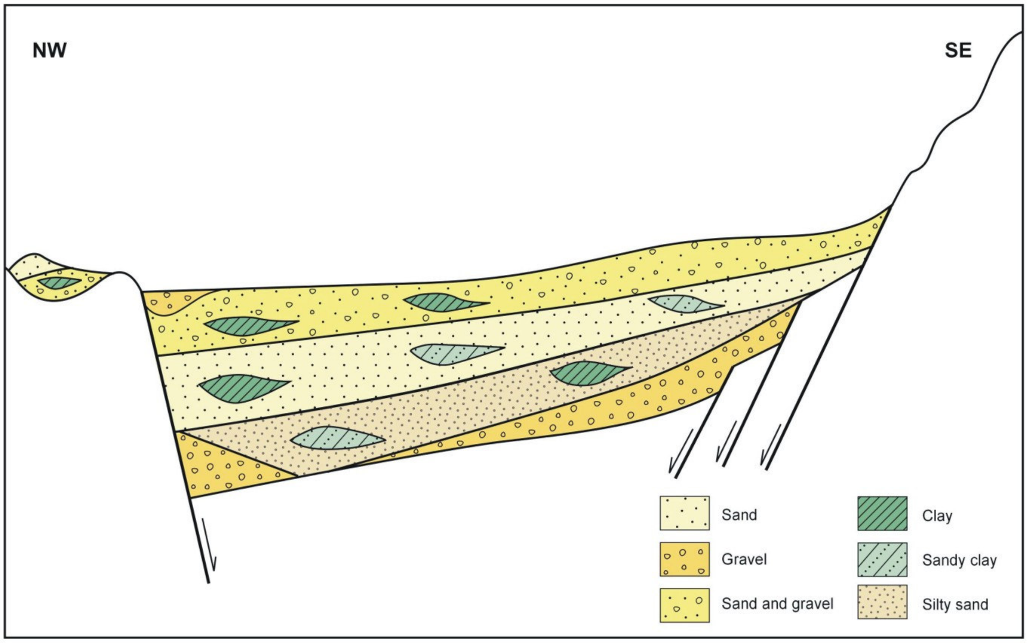


Figure 9 Schematic cross section showing the Quaternary sedimentary basin along the line shown in Figure 7.

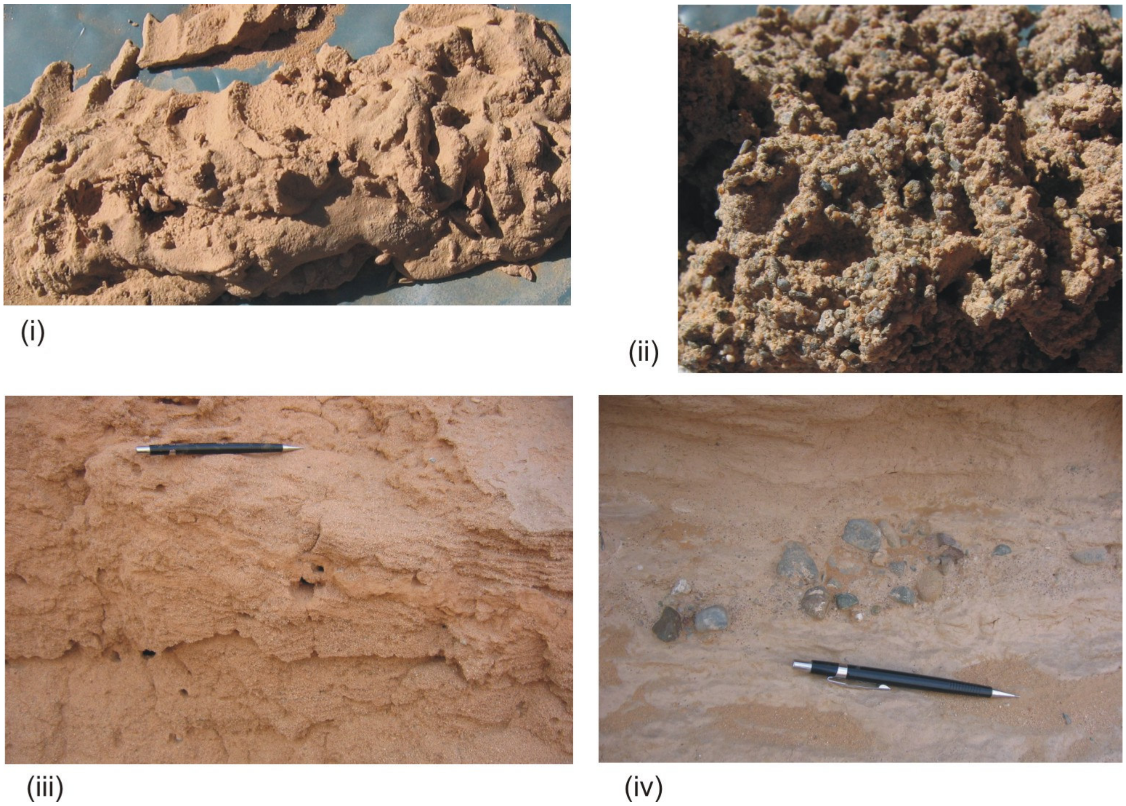

(i)
(ii)
(iii)
(iv)

Figure 10 Examples of Quaternary sediments in the Chahaertan aquifer. (i) fine grained sand and (ii) coarse grained sand from a newly drilled borehole; (iii) uniform fine to medium grained cross-bedded sand and (iv) pebble layer in fine to medium grained sand, both exposed in river bank.

4 Hydrogeology

The overall conceptual model of the hydrogeological system is described in this section. Some of the detail given here was derived from numerical groundwater modelling, which is described in Section 6 and Appendix 3.

4.1 AQUIFER GEOMETRY

The Quaternary aquifer on which Chahaertan lies extends from the Helan Mountains northwards to Jilantai and beyond (Figures 7 and 11). The aquifer varies from less than 30 m thick at its southeastern limit near the Helan Mountains, to more than 200 m thick around Chahaertan (Figure 9). The aquifer is bounded to the south and much of the east and west by low permeability Tertiary rocks that are effectively non-aquifers.

Without detailed groundwater level measurements across the aquifer it is not possible to exactly define the groundwater catchment, but it is likely to be approximately equal to the surface water catchment, which has been defined on the basis of the ground surface topography (taken from the DEM) (Figure 11). The approximate surface area of the aquifer is 1500 km^2.

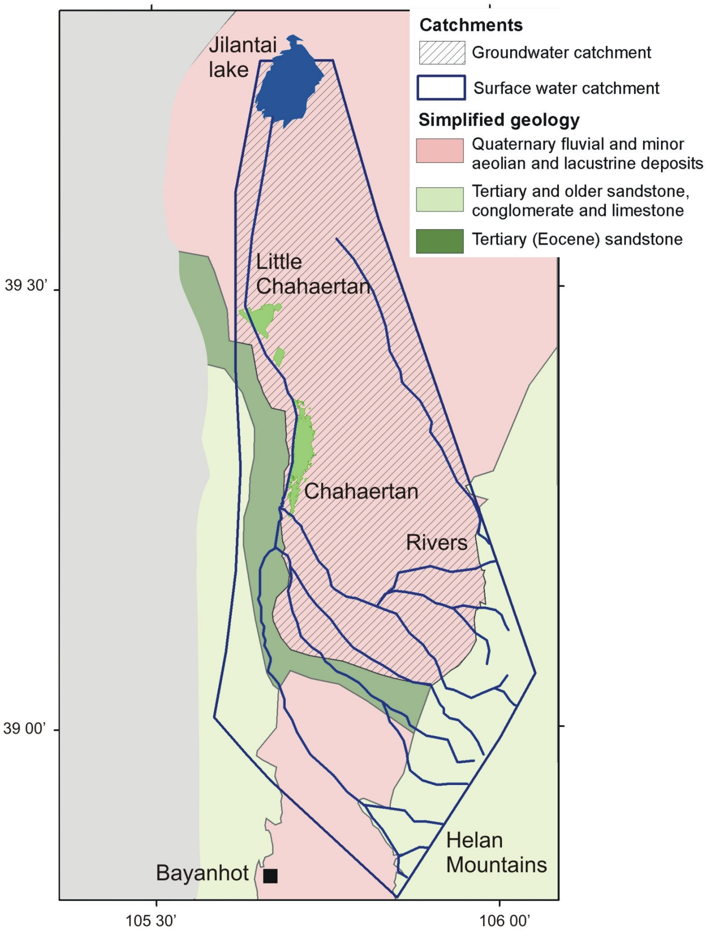


Figure 11 Schematic of hydrogeological system showing approximate surface water and groundwater catchment areas, simplified geology and rivers. Grey shading indicates outside the study area.

4.2 AQUIFER PROPERTIES

Some information on the aquifer properties of the Quaternary sediments of the basin and the adjacent Tertiary rocks is available from aquifer tests carried out during the 1970s and 1980s (Groundwater Development and Utilisation Teaching and Research Office, 1984; Yan and Wu, 1996).

There are various data available on hydraulic conductivity (equivalent to permeability), transmissivity and specific capacity from production wells. The data are summarised in Table 1. There is more information on horizontal hydraulic conductivity than on other aquifer properties. There is no information on aquifer storage coefficients.

The properties of the Quaternary aquifer are strongly influenced by the grain size variation of the sediment, which ranges from coarser-grained nearer to the mountains, to finer-grained further away, including the Chahaertan area. The coarser-grained deposits typically have higher hydraulic conductivity and transmissivity.

Table 1 Range in aquifer properties for different rocks in the study area

Aquifer Property	**Data sources**	**Southern part of Quaternary aquifer**	**Northern part of Quaternary aquifer**	**Tertiary rocks of the Helan Mountains**	**Tertiary rocks of the Tableland**	**Tertiary rocks below Quaternary aquifer**
Horizontal hydraulic conductivity ($m\ d^{-1}$)	10 individual data points for Quaternary [1,2]; unknown number of points for Tertiary [1,2]	5 – 30	2 – 10	0.01 – 0.3 (up to 5 in carbonate rocks)	0.3 – 1.2	0.01 – 1.5
Vertical hydraulic conductivity ($m\ d^{-1}$)	Unknown number of data points [1]	2 – 3				
Transmissivity ($m^2\ d^{-1}$)	10 individual data points [1,2]	600 – 1200	200 – 510			
Specific capacity ($m^3\ d^{-1}\ m^{-1}$)	unknown number of data points[3]	105		7	28	7

[1] Groundwater Development and Utilisation Teaching and Research Office, 1984

[2] Yan and Wu, 1996

[3] Hydrogeological map J-48-[10] (Appendix 1)

4.3 GROUNDWATER CHEMISTRY

4.3.1 Introduction

Twenty two wells in the Quaternary aquifer were sampled to assess groundwater chemistry. Most of the samples were taken from pumping irrigation wells in the period 5 to 13 September 2006. The location of the sample sites is shown in Figure 12. Sixteen sites were in Chahaertan oasis, two sites in Little Chahaertan, two sites at or near Jilantai, and one site in the herding area to the east of Chahaertan. Samples were taken for major and minor ion analysis, stable isotopes (δ^2H and $\delta^{18}O$) and CFC analysis. Field measurements were made of pH, dissolved oxygen (DO), redox potential (Eh), water temperature and specific electrical conductance (SEC).

Details of the sampling sites and the methods used for analysis, and selected analysis results for individual samples, are presented in Appendix 3. Full analysis results are presented on the accompanying CD-ROM.

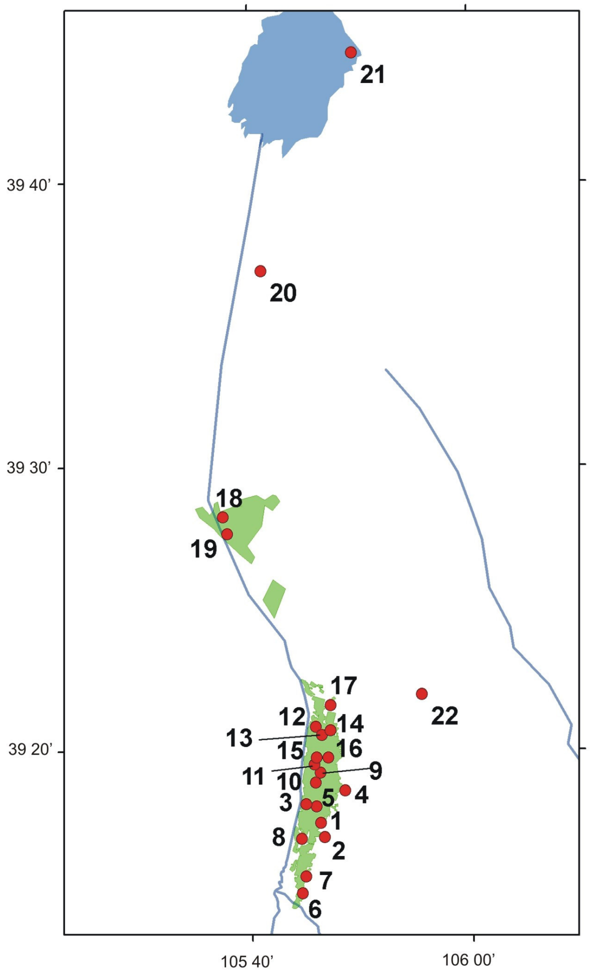


Figure 12 Locations of chemistry samples (sample numbers as given in Appendix 3).

4.3.2 Major and minor ions

Table 2 summarises the chemistry data for the 22 sites. Major ion data are summarised on a Piper diagram (Figure 14). Maps showing the distribution of NO_3 and SEC are presented in Figure 13. The main points are discussed below.

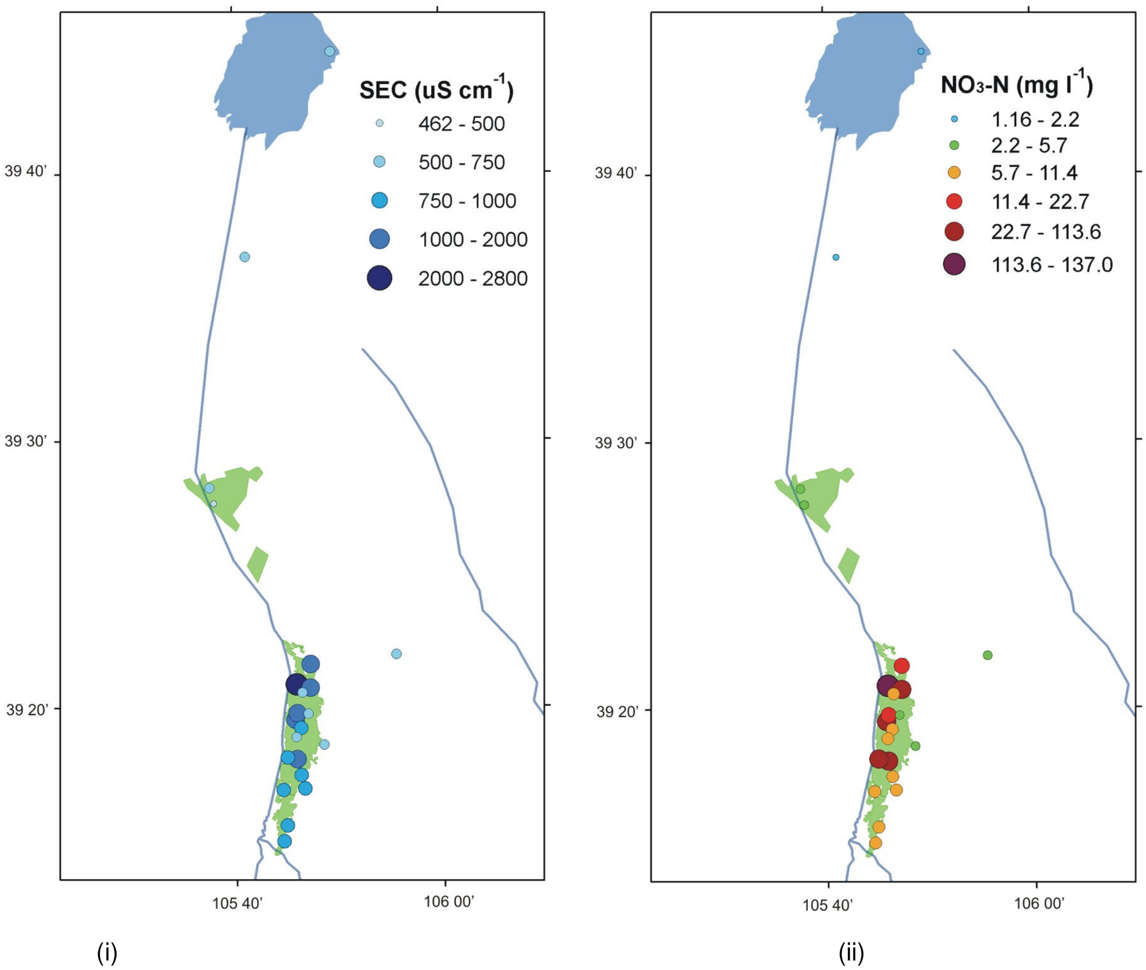
- Groundwater is moderately mineralised, with median total dissolved solids of 536 mg l^{-1} across the area and an interquartile range of 459 to 695 mg l^{-1}. The pH is slightly alkaline (median across area of 7.67). The temperature of the groundwater is 16.2 °C with an interquartile range of 15.7 to 17 °C. All samples within the Chahaertan area are oxygenated – only samples from the north of the area at Jilantai are reducing.
- Major ion chemistry in the aquifer is different in Chahaertan, Little Chahaertan and at Jilantai (Figure 14). Within Chahaertan, the cations are dominated by calcium (Ca)

and magnesium (Mg) and there is little variance in the Ca/Mg ratio. However, towards the discharge area at Jilantai, the dominant cation is Na, and the pH becomes more alkaline. There is no evidence that the groundwater becomes more saline towards the lake – the high concentrations of salt in the lakewater at Jilantai are caused by evaporation of discharging groundwater.

- There is a group of wells within the Chahaertan oasis that have elevated nitrate. These boreholes also have increased salinity, with elevated magnesium, calcium, chloride (Cl) and sulphate (SO_4) (Figure 15). All these wells are within the irrigated area, and may indicate significant degradation of the groundwater from excess fertiliser leached in irrigation returns.
- It is possible that the highest nitrate (and related chloride) concentrations may be related to additional nitrogen loading from point sources, specifically from animal waste and/or human sanitation. However, the overall amount of nitrogen loading from human sanitation and animal waste sources is thought to be a very small proportion (probably less than 1%) of the nitrogen loading from fertiliser.
- There is no evidence of arsenic (As) or fluoride (F) exceeding the WHO guideline values. Iron (Fe) and manganese (Mn) concentrations are also low across the aquifer.

Table 2 A summary of groundwater chemistry data for the Chahaertan oasis. More information is presented in Appendix 3.

		All data (22 samples)					**Chahaertan (16 samples)**				
Parameter	**Units**	**min**	**25%ile**	**median**	**75%ile**	**max**	**min**	**25%ile**	**median**	**75%ile**	**max**
Temperature	°C	15.0	15.7	16.2	17.0	21.6	15.0	15.7	16.0	16.4	17.8
SEC	µS cm^{-1} @ 25 ºC	462	675	823	992	2800	656	765	861	1274	2800
DO	mg l^{-1}	0.0	8.1	8.8	9.8	11.8	6.2	8.5	9.4	10.3	11.8
pH		7.39	7.60	7.67	7.80	8.63	7.39	7.59	7.65	7.69	7.98
TDS	mg l^{-1}	328	459	536	695	1925	447	524	560	802	1925
Cl	mg l^{-1}	43.8	92.2	108	158	369	65.1	103	111	192	369
SO_4	mg l^{-1}	34.8	80.2	93.8	122	314	69.0	89.8	103	137	314
HCO_3	mg l^{-1}	102	124	131	137	148	102	126	131	138	148
NO_3-N	mg l^{-1}	1.2	5.0	8.0	20.6	137	3.6	7.4	9.8	23.5	137
Ca	mg l^{-1}	13.3	65.0	76.3	99.7	281	64.7	71.0	83.9	120	281
Mg	mg l^{-1}	10.7	19.4	23.3	29.8	92.1	17.9	22.1	24.1	38.2	92.1
Na	mg l^{-1}	35.6	46.9	51.2	70.7	149	35.6	47.6	51.3	70.5	149
K	mg l^{-1}	2.20	2.91	3.00	3.31	5.17	2.63	2.98	3.03	3.34	5.17
Si	mg l^{-1}	4.03	6.32	6.45	6.69	6.87	6.28	6.40	6.47	6.72	6.87
Fe	µg l^{-1}	5.40	6.25	7.90	14.4	140	5.40	6.25	6.90	11.5	18.9
Mn	µg l^{-1}	0.14	0.34	0.49	0.97	12.1	0.15	0.35	0.43	0.89	3.70
As	µg l^{-1}	0.60	0.93	1.15	1.78	3.30	0.60	0.90	1.10	1.60	2.30
F	µg l^{-1}	148	230	249	299	596	148	227	242	262	370



(i) (ii)

Figure 13 SEC (i) and NO_3 concentrations (ii) in samples from the aquifer

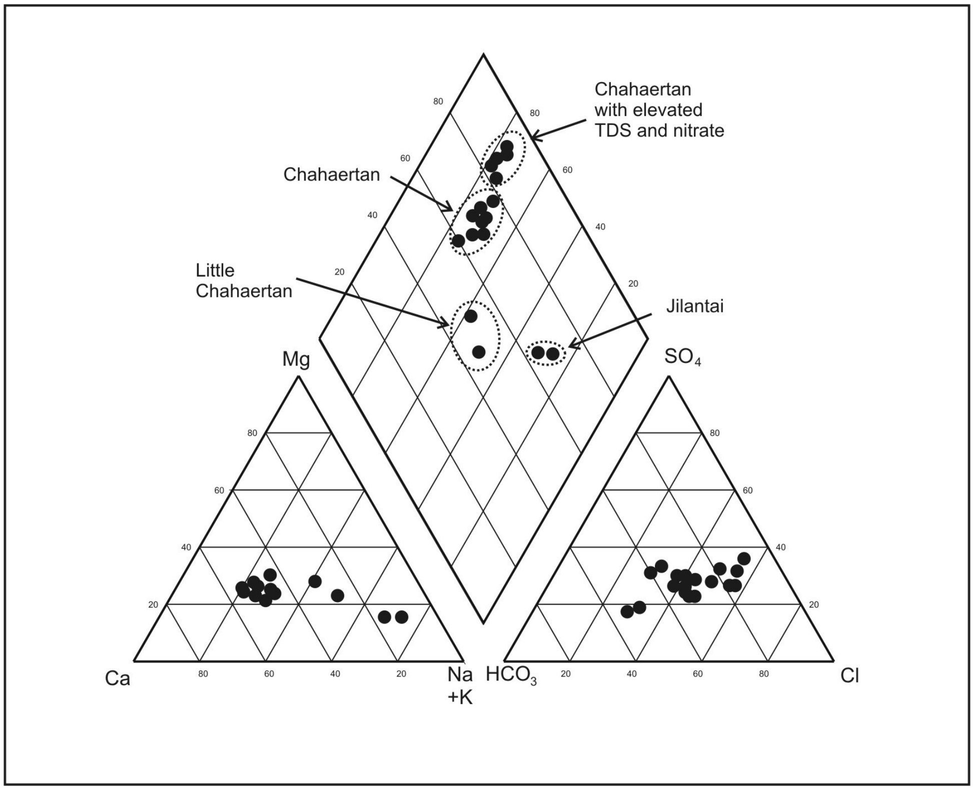


Figure 14 Piper diagram summarising major ion chemistry from the aquifer.

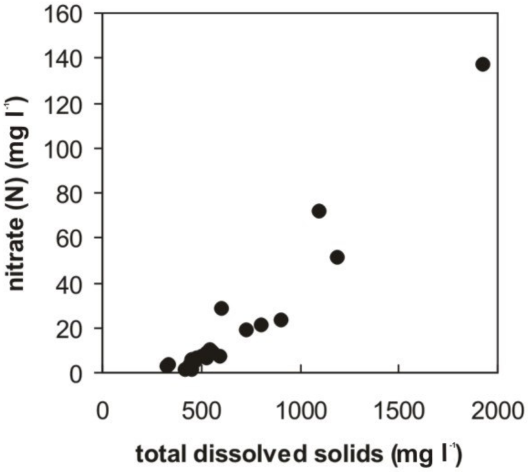


Figure 15 Nitrate concentrations plotted against total dissolved solids.

4.3.3 Stable isotopes and groundwater residence time

Identifying the age of groundwater in an aquifer can be a great aid in understanding the rate of recharge. For groundwaters, 'age' basically means the time a water has spent underground. There is no single way of dating water, but a range of techniques can be used to give a better idea of the likely age. In this project, chlorofluorocarbons (CFCs) and the stable isotopes δ^2H and δ^{18}O were used – these are relatively inexpensive methods and results can be gained quickly. Concentrations of chlorofluorocarbons (CFCs) have built up in the atmosphere since 1945 and measuring their concentrations in groundwater provides a way of determining the age or proportion of 'young' groundwaters. Oxygen and hydrogen stable isotopic composition are measured by mass spectrometry. These will usually show, albeit qualitatively, whether the water was recharged at a different temperature or altitude.

Stable isotopes δ2H and δ18O were taken for all sites, and samples for chlorofluorocarbon (CFC-11, CFC-12) at 13 sites. The data are given in the appendix, and the stable isotope data are plotted in Figure X relative to meteoric line for Yinchuan (106° 7' 48" E, 38° 17' 24" N: $\delta^2H = 7.22\ \delta^{18}O + 5.5$) (http://isohis.iaea.org/). The data are shown in Table 3.

The CFC data indicate detectable concentrations in all Chahaertan samples, but below detection values in Little Chahaertan. Towards Jilantai, one sample is also below detection, but the sample taken from the borehole below the lake has a small component – possibly as a result of mixing between groundwater and the lake water.

Therefore, active recharge within the past 50 years is occurring in Chahaertan. However, there is little or no evidence of active recharge in the past 50 years further northward towards Jilantai.

Table 3 Stable isotope and CFC data for Chahaertan.

			Conc^n (p mol)		**Modern Fraction**		**Year of Recharge**	
ID	**δ18O ‰**	**δ2H ‰**	**CFC-12**	**CFC-11**	**CFC-12**	**CFC-11**	**CFC-12**	**CFC-11**
1	-11.18	-76.7	0.43	0.21	0.22	0.06	1969	1962
2	-11.46	-82.1						
3	-11.02	-80.8	0.26	0.42	0.14	0.12	1966	1966
4	-11.04	-78.9	0.70	0.46	0.36	0.13	1974	1967
5	-11.55	-82.1						
6	-10.72	-81.2	0.15	0.13	0.08	0.04	1961	1960
7	-10.94	-78.9						
8	-11.03	-78.1	0.15	0.14	0.08	0.04	1962	1960
9	-10.94	-75.0	0.15	0.16	0.08	0.05	1962	1961
10	-11.08	-77.2						
11	-10.84	-77.4						
12	-11.24	-74.1	0.87	1.31	0.45	0.38	1976	1974
13	-10.91	-79.3	0.21	0.09	0.11	0.03	1964	1957
14	-10.82	-76.9						
15	-11.25	-77.6	0.33	0.29	0.17	0.08	1967	1964
16	-10.99	-78.9						
17	-11.10	-80.5	0.29	0.33	0.15	0.10	1966	1965
18	-12.60	-87.1						
19	-12.02	-83.0	0.00	0.00	0.00	0.00	<1948	<1948
20	-13.09	-89.9	0.00	0.00	0.00	0.00	<1948	<1948
21	-11.94	-82.5	0.38	0.37	0.19	0.11	1968	1965
22	-10.88	-79.6						

The stable isotope data indicate several samples which are significantly depleted in δ^2H and δ^{18}O (Figure 16). These correspond to the samples with no measurable CFC in Little Chahaertan and Jilantai. In relation to the local meteoric line at Yinchuan, many of the Chahaertan waters show signs of minor evaporative enrichment, consistent with an origin from river infiltration. By comparison, the values from Little Chahaertan and Jilantai may signify waters recharged during a wetter Holocene phase, or perhaps more likely, the product of mixing between an old end-member (> 10 000 years old) and younger water (perhaps several hundreds of years old). (In the Minqin Basin of the Gobi Desert, Edmunds et al. (2006) noted a depletion of around 4 ‰ in δ^{18}O for Pleistocene palaeowaters). The alternative explanation for isotopic depletion (increase in recharge altitude) would require a recharge source around 1000 m higher than the groundwater at Chahaertan, and can therefore be ruled out.

Further examination of the CFC and stable isotope data with the nitrate and major ion chemistry indicates some interesting trends, particularly if taken with the other studies on irrigation returns (Jerie 2006, Williams 2006a,b).

- Samples with elevated nitrate also show elevated TDS and all have CFC bulk ages of younger than 1966. These bulk ages do not necessarily indicate that the water was recharged in 1966. More likely is that bulk age indicates a contribution more modern water mixing with water that was recharged prior to 1950, or perhaps some resetting of the CFC “clock” due to re-infiltration of irrigation water. The main sources of nitrate in Chahaertan groundwaters is fertiliser application, as indicated from irrigation studies by Jerie (2006), and estimates of nitrogen loading from fertiliser (Williams 2006a). There may also be small point source inputs from animal waste and human sanitation, but these are not likely to be significant compared to the nitrogen loading from fertiliser. The increase in concentration of other major ions is likely to be largely due to the leaching of salts from the soil zone during the flood irrigation, although point source inputs of chloride may have a small effect. **The overall indication is that irrigation in Chahaertan is degrading groundwater quality in the basin, and that other wells will be affected in the future as the poor quality recharge from irrigation reaches the groundwater.**
- Wells that currently show no evidence of contamination from irrigation returns are isotopically similar to those that do show evidence of irrigation returns. They are not dominated by palaeowater, as seems to be the case at Jilantai and Little Chahaertan. **This implies that much of the water in Chahaertan is relatively young (up to perhaps several hundreds of years old) and therefore has been recharged under modern conditions. The most likely mechanism is from leakage from river flow.**

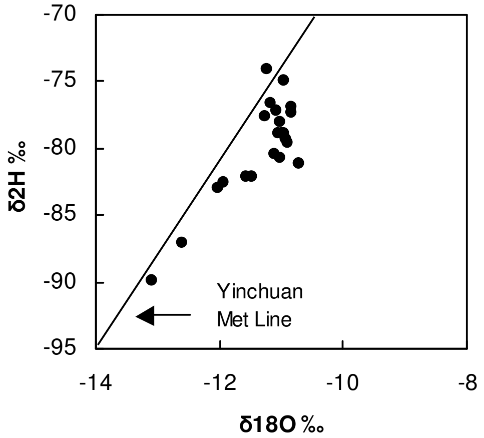


Figure 16 Stable isotope data for the aquifer. The most depleted waters are from Little Chahaertan and Jilantai.

4.4 RECHARGE

4.4.1 Introduction

Knowledge of the nature, volume and distribution of recharge across the aquifer is fundamental to understanding the groundwater system. Field observations in the Chahaertan area, the results of the chemistry survey carried out as part of this investigation, and comparisons with similar groundwater systems in other arid and semi arid areas indicate that there are likely to be three mechanisms of recharge to the Quaternary aquifer (Figure 17):

- **Direct rainfall recharge**, which occurs over the whole of the aquifer outcrop;
- **River leakage**, where water flowing in ephemeral river channels (mainly derived from rainfall in the Helan Mountains) infiltrates through the river beds into the aquifer; and
- **Irrigation returns**, which occur in the Chahaertan area.

The volume of recharge from each of these sources has been estimated (see below and Appendix 5). The estimates are based on very sparse available data, supported and tested by groundwater modelling.

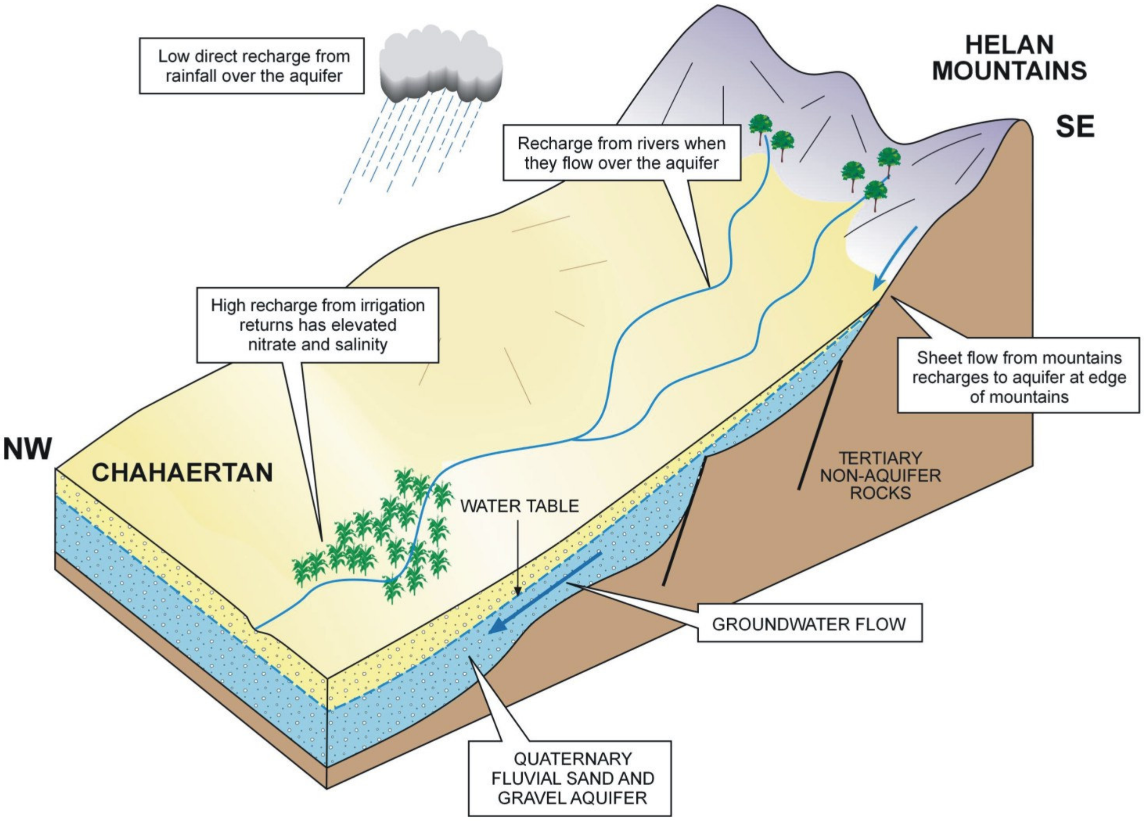


Figure 17 Illustration of different recharge types across the aquifer.

4.4.2 Direct rainfall recharge

Direct rainfall recharge to the aquifer is small, controlled by low annual rainfall and high evapotranspiration rates. The extent of evapotranspiration from the mainly sparse, shrubby vegetation, interspersed with significant amounts of bare ground, is unclear. Rainfall occurs as short lived, intense events: during the largest and longest rainfall events, rain can exceed evapotranspiration for a few hours, and recharge will occur.

Soils developed over the Quaternary aquifer are typically sandy and are have high infiltration capacities, and therefore little runoff. Areas of lower permeability soil do exist, possibly where thin hard crusts have developed, or where clay layers are present at or near the ground surface. These are evident as areas of surface water ponding after rain. However, these areas are small and are not likely to limit the available recharge significantly across the aquifer.

Using daily rainfall data and assuming a wetting threshold of 10 mm (the average daily evapotranspiration in the rainfall months), and little runoff a recharge model was developed (Appendix 5 and Section 5). This indicates that rainfall recharge to the aquifer accounts for an average of 15 mm a^{-1} across the aquifer, or a total of 20 Mm^3 a^{-1} across the aquifer outcrop. Rainfall recharge is greatest in the south where rainfall is highest.

4.4.3 River leakage

River flow infiltrating through the base of river channels is an important source of focussed local recharge to the aquifer. River flow is fed mainly by runoff from the Helan Mountains, where rainfall is highest, with only a small amount of inflow from runoff over the Quaternary aquifer (Section 3.3 and Appendix 5).

Leakage from the river channels to the Quaternary aquifer occurs along the length of the river channels wherever they directly overlie the aquifer. Two of the tributary channels of the main river system flow over Tertiary rocks for long stretches (Figure 11). Thin Quaternary deposits overlie the Tertiary rocks along much of these stretches, forming shallow local aquifers, and there will be some leakage from the rivers to these aquifers, but it is likely to be low compared to leakage to the main Quaternary aquifer. Leakage factors were estimated using the infiltration capacity of the soils and the dimensions of the rivers.

Groundwater modelling indicates that much of the leakage from the rivers happens over a short stretch of the main river channel adjacent to Chahaertan. This is immediately north of where the tributary channels join and the main channel flows onto the Quaternary aquifer from the Tertiary rocks (Figure 11 and Appendix 5). Recharge from river leakage accounts for the largest proportion of recharge in the Chahaertan area (Section 5 and Appendix 5).

There is other evidence to suggest the historical importance of river leakage to groundwater in the Chaheartan area. Before the river was diverted, much of the Chahaertan area used to flood. Hence a greater proportion of silt in the soil and the development of agriculature. The stable isotope data described above also seems to indicate a large proportion of water recharged in the past few hundred years, compared to further towards Jilantai where the water may be more than 10 000 years old.

Groundwater modelling indicates that river leakage provides between 20 and 650 mm a^{-1} locally, depending on the maximum river flow, or a total of 14 Mm^3 a^{-1} across the aquifer (Appendix 5 and Section 5).

4.4.4 Irrigation returns

Irrigation in Chahaertan is by means of flood irrigation, in most cases applied directly from the production well to fields by means of PVC low-pressure pipes or concrete-lined ditches. In a very few cases (thought to be less than 10), water is pumped from the well to a pond, which then feeds drainage ditches. In most cases, therefore, transmission losses between well and field are likely to be minimal. In those cases where water is stored in ponds, there is likely to be some infiltration through the base of the pond, but because the number of such cases is small, the total infiltration is likely to be low.

Flood irrigation is inefficient in terms of water use – in most such methods, only some 40% of applied water is used by crops (e.g. Wolff and Stein 1999). Investigations carried out as part of the ALERMP have showed that in Chahaertan the efficiency of irrigation is slightly higher – approximately 50% of applied water drains below the root zone, with water infiltration rates through the soil estimated at about 30 mm hr^{-1} (Jerie 2006). Lateral flow of this infiltrating water to the river is likely to be minimal, and so virtually all of this water will move down through the unsaturated zone to the water table to recharge the Quaternary aquifer.

The total volume of groundwater abstracted for irrigation in Chahaertan and Little Chahaertan has been estimated at between 18.5 and 21 Mm^3 a^{-1} (Section 4.5.2). Groundwater modelling indicates that recharge from irrigation returns in the Chahaertan oases is 350 mm a^{-1}, or a total volume of 10 Mm^3 a^{-1} (Appendix 5 and Section 5).

4.5 DISCHARGE

4.5.1 Natural discharge

The main natural discharge point for groundwater in the Chahaertan Quaternary aquifer is to the lake at Jilantai. Groundwater discharge is likely to be the largest input of water to the lake, because river flows only reach the lake during the largest rainfall events, probably only once or twice each year (Section 3.3). Discharge from the Chahaertan aquifer is not the only groundwater inflow to the lake – there will also be flows from other groundwater catchments. An estimate of evaporation from Jilantai lake, assuming annual evapotranspiration of 3000 mm and a lake area of 40 km^2, is 120 Mm^3 a^{-1}. This is the only available data constraining the volume of discharge from the Chahaertan aquifer, which must be significantly lower than 120 Mm^3 a^{-1}.

4.5.2 Groundwater abstraction from wells

Groundwater is abstracted from wells across the aquifer, but the main centre of abstraction is in the Chahaertan and Little Chahaertan oases. Away from these irrigated areas, there are an unknown number of low yielding wells, mainly used by herders. A number of these are likely to have become disused since 2005 when a grazing ban was established across large parts of the aquifer. Even taken together, they are likely to represent a very small proportion of the total groundwater abstraction from the aquifer.

As described in Section 1.3, there are currently 168 production wells in the Chahaertan oases: 119 in Chahaertan and 49 in Little Chahaertan (Figure 18). The total number of wells currently in operation is uncertain, but it is likely that approximately 110 wells in Chahaertan and over 40 wells in Little Chahaertan are in use every year.

Current groundwater abstraction from Chahaertan and Little Chahaertan was estimated as part of the study. Four different methods were used, in order to increase confidence in the result. The details of the calculations are presented in Appendix 4. Total abstraction from the oases is estimated at 18.5 to 21 Mm^3 a^{-1}: 16 Mm^3 a^{-1} in Chahaertan and 2.5 to 5 Mm^3 a^{-1} in Little Chahaertan (Appendix 4).

Most of the production wells are used for irrigation and the annual pumping regime is similar for all of them. The wells are typically pumped at rates of between 60 and 80 m^3 hr^{-1} for between 12 and 20 hours each day, for a period of one to two weeks in March or April, and then for at least 25 days each month from early May to late August, and into early September in dry years. A few wells pump for only 15 to 20 days each month during this period. Most are also pumped for a period of approximately one week in December. A few wells – probably less than 15 – are used for drinking water, typically for a number of different households, and are pumped daily (typically for five to seven hours each day) at low rates all year round.

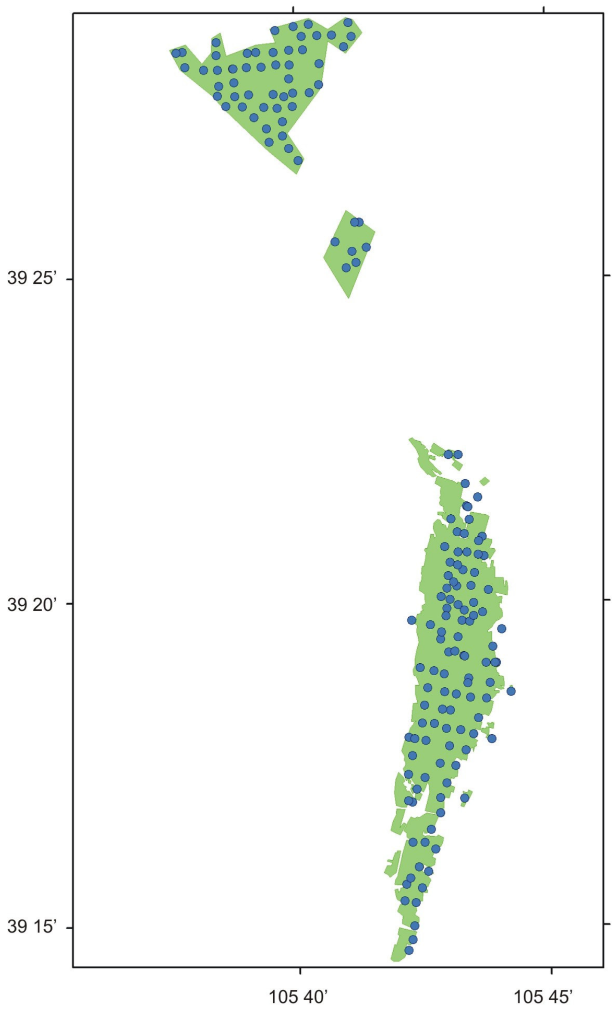


Figure 18 Location of production wells in the Chahaertan oases

4.6 GROUNDWATER FLOW

The dominant groundwater flow direction in the aquifer is from south to north, as indicated by the available groundwater level measurements (Section 4.4) and the results of groundwater flow modelling (Section 5 and Appendix 5). Flow is towards the main natural discharge point for the aquifer at Jilantai salt lake.

The rate of groundwater flow through the aquifer has been estimated using Darcy's Law at between 0.015 and 0.03 m d^{-1}. This assumes an average hydraulic gradient of 0.003 (Yan and Wu 1996) and an average hydraulic conductivity of 5 m d^{-1}. At these flow rates, it would take groundwater between 3 000 and 6 000 years to flow from the southern edge of the aquifer to Chahaertan, and more than 10 000 years to flow from the southern edge of the aquifer to Jilantai. However, as discussed above, leakage from river flow allows modern recharge to move much more rapidly in the northern part of the aquifer.

Groundwater movement through the unsaturated zone is likely to be slow, partly due to the presence of low permeability clay and silt bands (Section 3.4), which despite not forming persistent layers, are likely to cause vertical groundwater flow paths to be tortuous and elongated. Although no direct data are available, interpretation of the available hydraulic properties and chemistry data indicates that vertical unsaturated groundwater movement may be as slow as 2 m yr^{-1}. For example there are some wells where elevated nitrate and TDS have not been measured, despite parts of Chahaertan having been developed for 40 years.

4.7 GROUNDWATER LEVELS

Very few data on groundwater levels in the Quaternary aquifer are available outside of Chahaertan. One measurement from a well in the southeast of the aquifer near the Helan Mountains is available on the hydrogeological map (J-48-[10]; Appendix 1; Appendix 5). An artesian well in the north of the aquifer 9 km south of Jilantai gives a second data point (Appendix 5). For most of the aquifer, there is no information to show whether groundwater levels have changed over time.

The only known long term groundwater level data for the aquifer is from monitoring wells in Chahaertan, which have been in use since before 1984. The Chahaertan groundwater development report stated that by 1984, groundwater levels in the oasis were declining at a rate of 0.17 to 0.76 m a^{-1} (Groundwater Development and Utilisation Teaching and Research Office, 1984).

Water level data from seven monitoring wells in the Chahaertan oasis, taken by the now-defunct Water Management Station, are available for 1984 to 1994. According to reports from ex-Water Management Station staff, water level monitoring stopped after 1994. In 2004, responsibility for groundwater level monitoring in Alxa League passed to the newly-formed Hydrology and Water Resource Survey Bureau. According to verbal reports from this Bureau, water levels have been measured four times per year in three of the monitoring wells in Chahaertan since 2004, but none of these data were made available to the current study.

Six of the monitoring wells still exist and water levels in these wells were measured during the current study in September 2006. The locations of these wells are shown in Figure 19. Available groundwater levels in these six wells, as elevation above ground level, are shown in Figure 20. The depth of groundwater level below ground level (mbgl) becomes less from south to north in the oasis, as ground surface elevation falls in this direction. The groundwater level in the southernmost monitoring well is 77 mbgl (ground surface elevation is 1202 m); in the northernmost monitoring well (at the north of Chahaertan) it is 45 mbgl (ground surface elevation is 1163 m), and in Little Chahaertan groundwater levels in production wells on drilling were reported by well owners to be 20 to 25 mbgl (ground surface elevation 1090 to 1105 m).

Groundwater levels respond to pumping in the oasis: they fall from April to July or August, which is the main period of pumping, and recover from September to March, during which time there is little pumping. Groundwater levels also fall during the short winter irrigation in December (e.g. Mu Cao Chang Monitoring Well). Mu Cao Chang Monitoring Well is in one of the most intensively pumped parts of the oasis, and it shows the largest seasonal water level fluctuation. The monitoring well furthest from the main area of pumping in the oasis is Outside the Fence Monitoring Well, and this well shows the smallest seasonal water level fluctuations, indicating that it is least affected by pumping.

Water levels in the monitoring wells dropped by between four and six metres between 1984 and 1994, and by a total of between six and ten metres over the 22 years between 1984 and 2006. This is an annual average decline over the 22 years of between 0.27 and 0.45 m. The regular and continuous decline in water levels indicates that abstraction from the oasis is greater than recharge.

During the current study, three new monitoring wells were sited in Chahaertan and Little Chahaertan, in areas where there is a gap in water level information (Figure 19). Data from these new wells will complement information from the existing wells and allow accurate assessment of groundwater level behaviour in the oases.

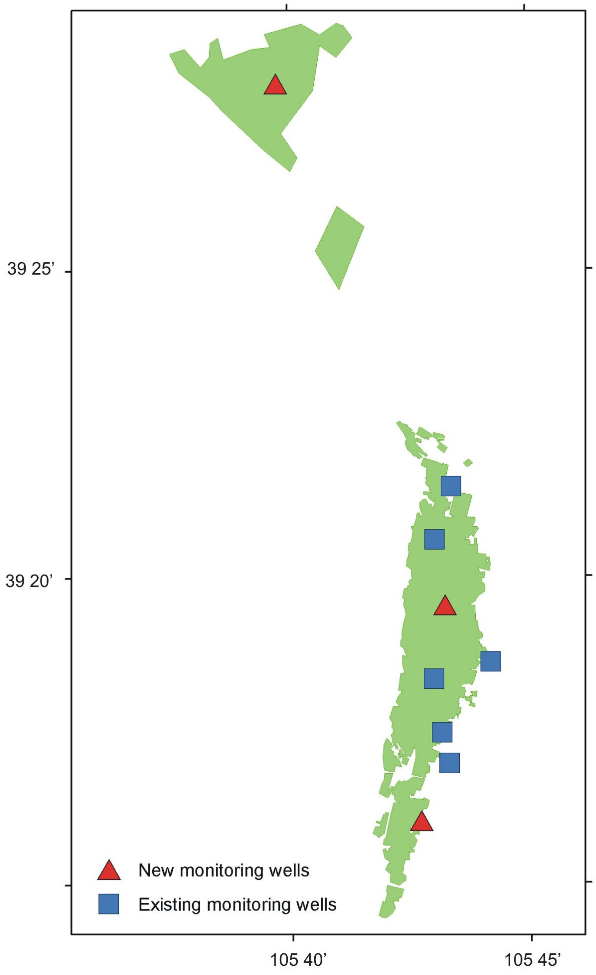


Figure 19 Location of existing and proposed new monitoring wells in the Chahaertan oases

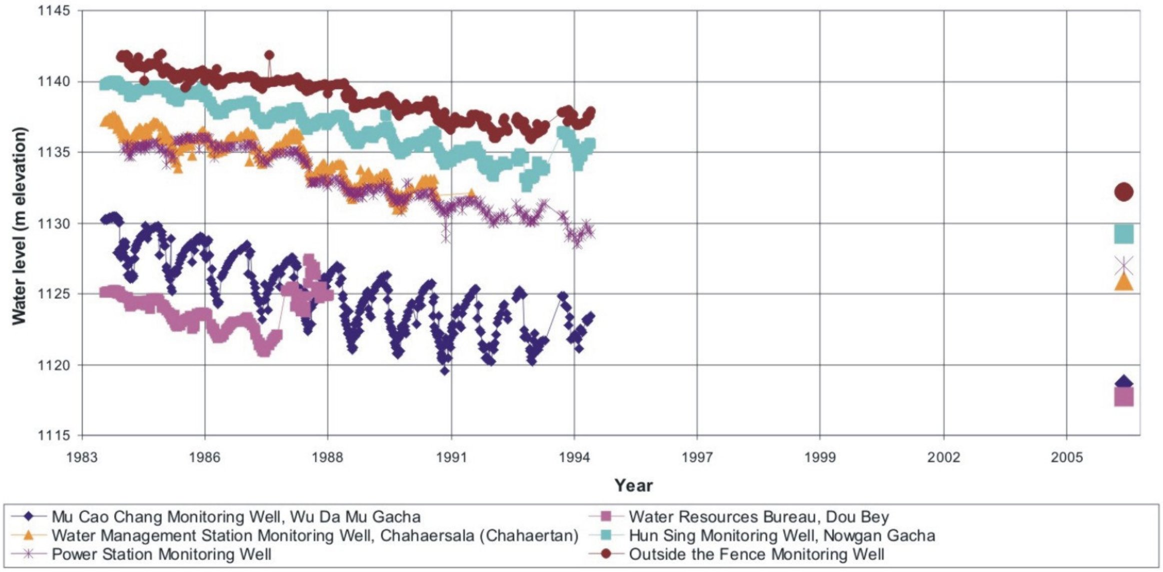


Figure 20 Groundwater levels in six monitoring wells in Chahaertan oasis, 1984 to 1994, with a single measurement in September 2006.

5 Groundwater modelling

The development of the groundwater model for the Chahaertan aquifer is described in detail in Appendix 5. This section summarises the results of the modelling.

5.1 RECHARGE MODEL

5.1.1 Introduction

Distributed recharge models are now often constructed for use with groundwater models. They allow the identification and quantification of recharge processes. Both direct (i.e. soil-based) and indirect (e.g. runoff recharge) processes can be quantified. Other recharge mechanisms, such as urban losses from water mains and sewers, and irrigation returns, can also be included. The main issue with recharge models is the validation of the amount of recharge estimated by the model. Since recharge is difficult to measure directly, the reliability of a recharge model must be tested by comparing the results with a detailed water balance or by comparing time series of recharge with groundwater level hydrographs.

5.1.2 Results

The recharge model simulated recharge from three sources: directly from rainfall, from river leakage and from irrigation returns.

The total volume of recharge to the aquifer is low, at 44 $Mm^3\ a^{-1}$, but river leakage and irrigation returns provide significant local recharge. Although they only occur in small areas (Figure 22), together they make up more than half the total volume of recharge across the whole aquifer.

• Recharge from rainfall	20 $Mm^3\ a^{-1}$
• Recharge from river leakage	14 $Mm^3\ a^{-1}$
• Recharge from irrigation returns	10 $Mm^3\ a^{-1}$

Over most of the aquifer the only available recharge is from rainfall, and annual recharge averages less than 20 mm (Figure 22). This is in the range of recharge estimates from other semi arid and arid areas in China and elsewhere (Edmunds et al. 2006, Scanlon et al. 2006). In the irrigated oases of Chahaertan and Little Chahaertan, recharge from irrigation returns is far larger, at 350 mm a^{-1}. Along the river channels, river leakage increases recharge to between 20 and 650 mm a^{-1}, depending on the maximum river flow (Figure 21). The highest rate of recharge from river leakage is to the immediate southwest and along the western edge of the Chahaertan oases, just downstream of the point where the rivers merge and the river flows are highest.

It is difficult to quantify exactly local recharge to the area around Chahaertan, largely because of uncertainty in defining the size of this area. However, the local recharge is likely to be less than 18 $Mm^3\ a^{-1}$. This includes all of the recharge from irrigation returns (10 $Mm^3\ a^{-1}$), approximately 6 $Mm^3\ a^{-1}$ from river leakage, and less than 2 $Mm^3\ a^{-1}$ from rainfall recharge. Significantly, even the higher end of this estimate is less than calculated groundwater abstraction from the oasis.

The importance of local recharge, from river leakage and irrigation returns, is supported by the groundwater chemistry. The CFC and stable isotope data indicate that active recharge (within the past 50 years) is occurring in Chahaertan, but that further north towards Jilantai, where river flows are smaller and less frequent, there is little or no evidence of active recharge in the past 50 years.

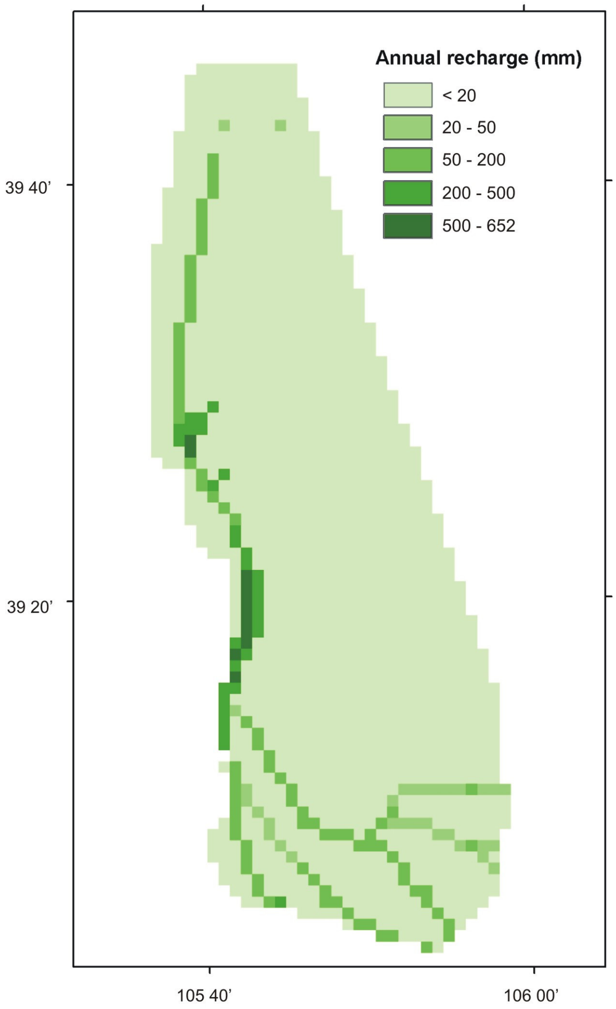


Figure 21 Spatial distribution of modelled recharge across the aquifer

5.2 GROUNDWATER FLOW MODEL

5.2.1 Introduction

The main output from the modelling element of this project has been a steady state groundwater flow model, which uses average recharge and abstraction that do not change over time. A groundwater flow model allows the water balance to be tested against measurements of groundwater head. A steady state model allows a realistic simulation of the groundwater system to be developed and tested, including parameters such as aquifer thickness, permeability and recharge inputs.

A dynamic balance model was also developed for the Chahaertan aquifer. This is a precursor to a time variant model, and uses recharge and abstraction data that vary throughout a single year, but do not change from year to year. A dynamic balance model is used to test whether the steady state model provides a reasonable simulation of how the groundwater system behaves with time.

A time variant model was not produced during this study, because there are not sufficient available data to warrant its development. A time variant model needs long term historical data series, including recharge (i.e. requiring long term rainfall and evapotranspiration time series), abstraction and natural groundwater discharge, which are not available for the Chahaertan aquifer.

5.2.2 Results

The steady state groundwater flow model has improved our understanding of the Chahaertan groundwater system, confirming that the available permeability and aquifer thickness data are broadly correct, and just as importantly, constraining the recharge model.

The model was refined so that the modelled groundwater head distribution fits as closely as possible the available groundwater level data for the aquifer. These data are mainly available in the Chahaertan area, with rare data from elsewhere. Overall the data give a reasonably good fit, to within 10 m in the north of the model and within 15 m at the south of Chahaertan – or within 8 to 12% of the observed head variation across the model. The inflows and outflows to the model balance well, increasing confidence in the model results.

The dynamic balance model simulated the typical annual variation in groundwater level in the Chahaertan oasis well, confirming that the steady state model is a reasonably good representation of the Chahaertan aquifer system (Appendix 5).

5.3 WATER BALANCE

The modelled water balance has helped to increase confidence in the recharge model and highlighted some significant aspects of the Chahaertan groundwater system. It should be recognised that all the elements of the water balance are estimated, based on varying amounts of data, and that there may be a large margin of error in each of the estimates, so that the overall potential margin of error is large. The overall modelled water balance is summarised in Table 4. This indicates that recharge to the groundwater system is low, as would be expected in an arid to semi arid area. Modelled discharge to Jilantai lake, which is the main natural discharge from the groundwater system, is not much higher than groundwater abstraction from Chahaertan, indicating that abstraction is a significant output from the system. The modelled figures suggest that abstraction at Chahaertan may have reduced the volume of flow to the lake.

Table 4 Summary of modelled steady state water balance

Parameter	**Value**
Total recharge ($Mm^3 a^{-1}$)	44.26
Total boundary inflow ($Mm^3 a^{-1}$)	0
Total boundary outflow ($Mm^3 a^{-1}$)	0
Total abstraction ($Mm^3 a^{-1}$)	18.40
Total natural discharge ($Mm^3 a^{-1}$)	25.81

The significance of groundwater abstraction as a large proportion of total output from the groundwater system is supported by the available data on groundwater levels, which indicate that groundwater abstraction in Chahaertan is greater than local recharge (Section 4.7).

6 Groundwater management

6.1 INTRODUCTION

The reason for studying and modelling the groundwater system in the Chahaertan oasis was to identify how sustainable the groundwater abstraction is, and to identify any degradation of the groundwater. In this section we highlight the issues that have come to light during this study and suggest options for managing the aquifer.

6.2 GROUNDWATER ISSUES

The main issues in Chahaertan are the following:

- Water levels are declining across the irrigated area at approximately 0.3 to 0.5 m per year. The reason for this is that locally groundwater abstraction (approximately 20 Mm^3 a^{-1}) exceeds the local recharge (natural recharge from river flow in the vicinity is less than 10 Mm^3 a^{-1}). If water levels continue to decline at this rate, many wells will be unusable within 30 to 50 years.
- The amount of water used for irrigation in Chahaertan and Little Chahaertan may be equivalent to 50% of the current annual recharge to the entire Quaternary aquifer. Abstraction for irrigation may in time reduce flows to the Jilantai salt lake.
- The diversion of the river channel to protect the Chahaertan irrigated area is likely to have reduced natural recharge to the aquifer at this point.
- Diffuse contamination from excess fertiliser leached into the aquifer in irrigation returns is seriously degrading the quality of the groundwater at Chahaertan. In wells with a high proportion of modern water (recharged since 1966), nitrate concentrations are highly elevated (20 to 130 mg l^{-1} NO_3 as N), and salinity (i.e. TDS) has increased.
- Point source contamination from animal waste or human sanitation may contribute to nitrogen loading in some areas. However, the overall nitrogen input from these sources is likely to be very small compared to the input from fertiliser.
- There is no evidence for direct contamination of production wells by water, fertiliser or sanitation waste leaking down the casing of poorly constructed wells. All the production wells seen during this study appeared to be suitably constructed with low vulnerability to direct contamination.
- Given the nature of the Quaternary aquifer, in which groundwater movement is relatively slow, there is a lag time between cause and effect. Therefore, there is likely to be poor quality water within the unsaturated zone, which as it reaches the water table, will continue to degrade water quality in the aquifer for tens of years.

6.3 MONITORING

To effectively manage the aquifer at Chahaertan it is essential to monitor the groundwater system. Only with this information will it be possible to test whether the management options are working.

1. As part of ALERMP, six monitoring boreholes have been repaired and three new boreholes drilled in key locations. Water levels in these boreholes must be measured every month to assess the decline in water levels across the aquifer.

2. The variation in nitrate concentrations and salinity in Chahaertan is a cause for concern. To truly understand aquifer behaviour, both these parameters should be monitored three times a year: at the first irrigation of the year, midway through irrigation, and at the last irrigation. We suggest that at least 10 wells are monitored and are chosen from the 22 sampled for this study. They must be pumping at the time of sampling. Five high nitrate, high salinity wells should be chosen, and five low salinity, low nitrate wells. A reliable indication of water salinity (or total dissolved solids) can be obtained easily by measuring the SEC (Figure 22).
3. To help build confidence in any future time-variant groundwater model, daily rainfall data and river flows are needed for the study area. Daily rainfall data may exist for the area, but were not accessible during the project. River flows could be measured by spot gauging flows at several locations along the course of the river during rainfall events.
4. Monitoring data must be stored, reviewed and communicated to all relevant institutions. There are complicated institutional issues about who would take on such a role, but in the past, groundwater monitoring in Chahaertan was most effective when undertaken at a local level and the results communicated upwards to regional level.

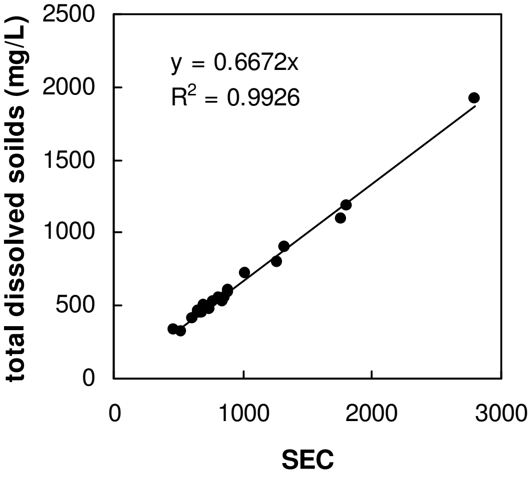


Figure 22 There is a direct positive relationship between total dissolved solids (i.e. salinity) and SEC in groundwater in Chahaertan. Salinity can therefore be monitored by measuring SEC.

6.4 MANAGEMENT OPTIONS

As discussed above, monitoring of groundwater levels and water quality, and the regular review of this information, is fundamental to any options for managing groundwater in Chahaertan. The following are required to protect groundwater resources from further degradation:

1. There should be no further abstraction wells drilled in Chahaertan. Current abstraction already exceeds local natural recharge.
2. Abstraction from existing wells should be reduced to halt the decline in groundwater levels and minimise returns from irrigation. Irrigation returns degrade the quality of the groundwater in the aquifer. Work by Jerie (2006) indicates that abstraction should be reduced by 30% to minimise drainage of excess irrigation water. Jerie (2006) and

Williams (2006) indicate that a reduction in water and fertiliser use may not have a significant impact on crop yield, and may in fact increase gross margins.

3. Fertiliser and pesticide use should be controlled. With some wells showing nitrate concentrations in excess of 130 mg l^{-1} NO_3 as N, the indications are that excess fertiliser is being used and is being leached to the aquifer. As well as a reduction in the volume of irrigation water, there should be a reduction in the amount of nitrogen fertiliser used, in order to minimise nitrate leaching.
4. Consideration could be given to increasing recharge from river flow to the south of Chahaertan by constructing a recharge lagoon. This would simulate the natural predevelopment system, when the aquifer may have received considerably more recharge from river leakage. This however, may involve considerable engineering and may not be cost-effective.
5. The catchment must be treated and managed as a whole. The impact of abstraction and any modifications to river channels will have an effect on the Jilantai salt lake and corresponding salt works. Therefore, the impact of any measures taken in Chahaertan on the catchment as a whole must be taken into consideration.

Appendix 1 Data sources

The following data sources were consulted as part of the groundwater investigation. Where relevant, notes on the sources are provided.

Reports:

ALERMP. 2002. Ground and Surface Water Resources Report. ACIL/URS, November 2002. *Project report on water resources across Alxa League. No specific information on Chahaertan.*

People's Liberation Army. 1976. Regional Hydrogeological Survey Report for Sheet J-48-[4]: Ji Lan Tai. *Sheet description for hydrogeological map. Information on aquifer properties, groundwater levels, well yields, groundwater chemistry.*

People's Liberation Army. 1980. Regional Hydrogeological Survey Report for Sheet J-48-[10]: Alxa, Left Banner. *Sheet description for hydrogeological map. Information on aquifer properties, groundwater levels, well yields, groundwater chemistry.*

Groundwater Development and Utilisation Teaching and Research Office. 1984. Hydrogeology Survey Report on Chahaertan Irrigation Area, Left Banner: Water Resource Assessment and Systematic Analysis. Produced within the Agricultural and Animal Husbandry, Water Conservancy and Engineering School of the Inner Mongolia Agricultural and Animal Husbandry College, December 1984. *Groundwater development report on Chahaertan oasis.*

Yan Lianju and Wu Shengxhang. 1996. Groundwater Systems in Arid Areas: Western Helanshan Groundwater Systems Research. Geography Publishing House. *Hydrogeological study of the whole of the western Helanshan area, including Chahaertan.*

Jerie P. 2006. Improving the Management of Water and Nitrogen Fertilizer for Agricultural Profitability and Groundwater Quality in Alxa. Preliminary ALERMP Report, June 2006. *Internal ALERMP/AusAID report.*

Maps:

People's Liberation Army. 1976. Hydrogeology map of Sheet J-48-[4]: Ji Lan Tai. 1:200 000.

People's Liberation Army. 1980. Hydrogeology map of Sheet J-48-[10]: Alxa, Left Banner. 1:200 000.

Topographical maps at 1:200 000 scale for Ji Lan Tai and Alxa: Left Banner (Bayanhot) sheet areas. Paper and GIS. Source unknown.

Quickbird image of Chahaertan oasis. *Detailed satellite image, captured expressly for the ALERMP project. Not available for Little Chahaertan.*

Digital Elevation Model (DEM) at 90 m resolution, from NASA. *Freely available via the Internet.*

Records:

Alxa League Left Banner. 2002. Water Resource Report. *Table of results from an incomplete well survey in Chahaertan and Little Chahaertan.*

Left Banner Water Management and Water Resource Office. 1992. Water Supply Project (Supply Amount) Yield Statistics Summary Table. Alxa, Left Banner, Inner Mongolia, December 1992. *Table of results from a survey of production wells in Chahaertan and Little Chahaertan.*

Well records for 49 wells in Chahaertan drilled between 1977 and 1996. *Well records for all the production wells in the Chahaertan oases were not seen during this investigation. It is not known if they are available or not.*

Example of Water Abstraction Licence for an irrigation borehole. Well Number 95-004.

Alxa Meteorological Data. Published data for different stations in Alxa. *Long term average and monthly average rainfall and evapotranspiration for 1954 to 1980; also incomplete daily rainfall for 2003 to 2005.*

Comprehensive Extension Station. Daily rainfall data for summer 2006. *Partial, informal record of daily rainfall from June to August 2006.*

Appendix 2 Climatic data

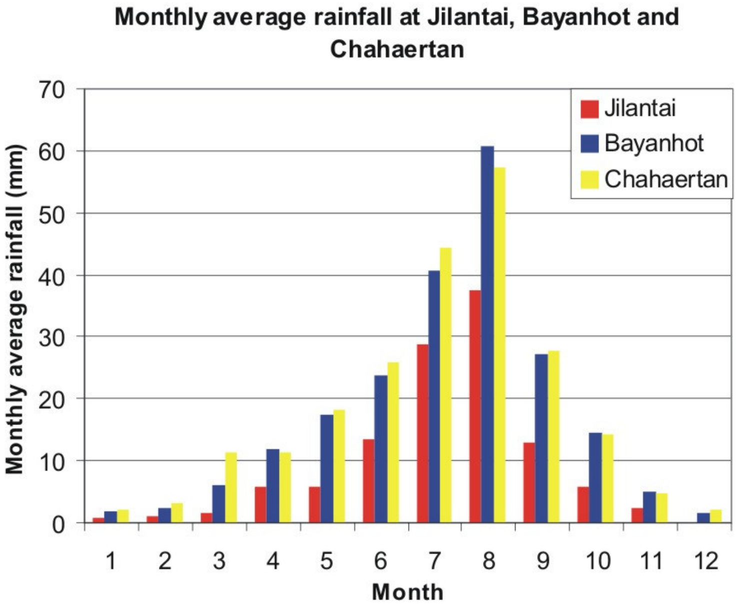


Figure 23 Monthly average rainfall for Jilantai, Bayanhot and Chahaertan, 1954 to 1980 (Alxa Meteorological Office).

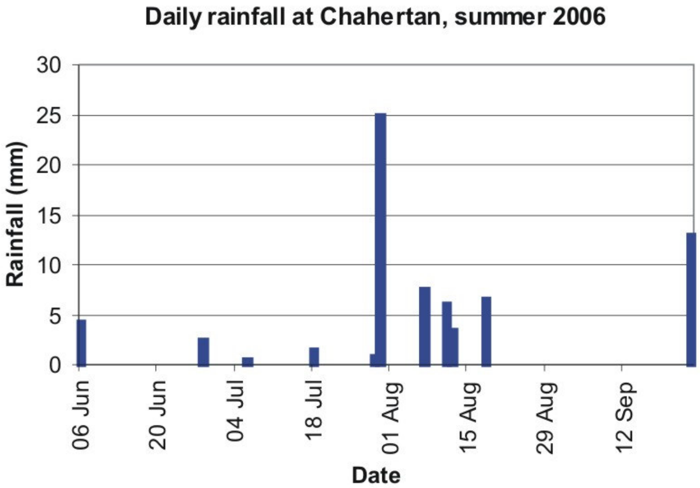


Figure 24 Limited series of daily rainfall data for Chahaertan (Comprehensive Extension Unit, supplemented by data from raingauge managed by farmer).

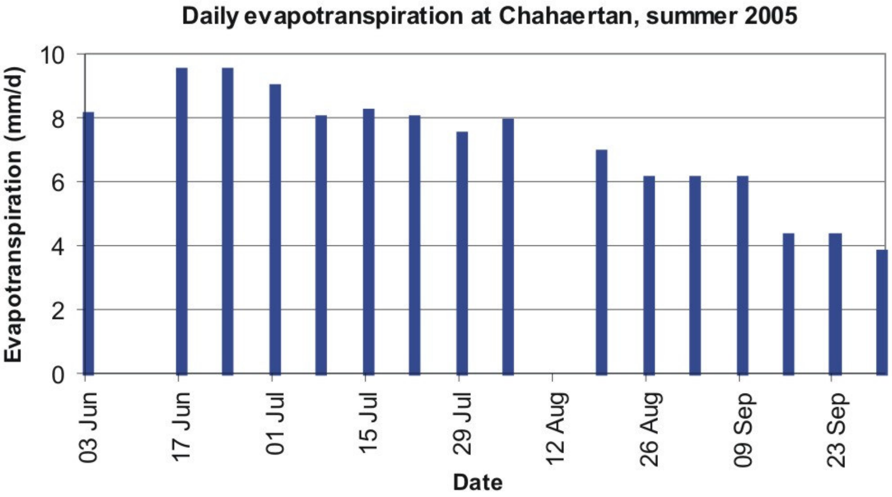


Figure 25 Limited series of daily evapotranspiration data for Chahaertan, averaged over 10-day periods (Jerie 2006).

Appendix 3 Groundwater chemistry sampling and results

SAMPLING PROCEDURE

Most of the boreholes investigated had been pumped regularly in the few weeks leading up to sampling, and were pumping at the time of sampling. Where boreholes were not pumping on arrival, they were pumped for at least 20 minutes to allow the borehole to be purged.

At each sample site, field measurements were made of pH, dissolved oxygen (DO), redox potential (Eh), water temperature and specific electrical conductance (SEC). Where possible, pH, DO and Eh were measured in an in-line flow cell to minimise atmospheric contamination and parameters were monitored (typically for 10 to 15 minutes) until stable readings were obtained. Where not possible, measurements of water direct from the pump outlet were made in a bucket within one to two minutes of abstraction.

Water samples were collected from each site for subsequent laboratory analysis. Samples for major- and trace-element analysis were filtered through 0.45 μm filters and collected in polyethylene bottles rinsed with sample water before collection. Four filtered aliquots were collected at each site: two were acidified to 1% v/v with Aristar HNO_3, one for analysis of major cations, total sulphur and Si by ICP-OES (inductively coupled plasma-optical emission spectroscopy), and the other for a large range of trace elements by ICP-MS (inductively coupled plasma-mass spectrometry). A third aliquot was acidified to 1% v/v with Aristar HCl for analysis of As by AFS (atomic fluorescence spectrometry) with hydride generation. A fourth aliquot was left unacidified for analysis of anions by ion chromatography (NO_3-N, Br, F); automated colorimetry (Cl, NO_2-N, NH_4-N) and HCO_3.

Additional samples were collected in glass bottles for stable-isotopic analyses (δ^2H and $\delta^{18}O$). At 13 of the sites, a sample was also collected for CFC analysis in a glass bottle, submerged under flowing groundwater to prevent atmospheric contamination. Most analyses were carried out at the BGS laboratories in Wallingford, except for ICP-MS analysis which was carried out by ACME laboratories, Vancouver, Canada.

Analyses of total sulphur are hereafter expressed as SO_4 and alkalinity as HCO_3. Nitrate is expressed NO_3-N. Analyses of δ^2H, $\delta^{18}O$ are expressed as per mil deviations relative to VSMOW (Vienna Standard Mean Ocean Water)

Table 5 Summary of wells sampled during chemistry investigation

ID	Well name	Location	Easting	Northing	Altitude (m)	Well depth (m)
1	Zhang Zhong's Well, Nowgan Gacha	Chahaertan	105.7187500	39.2910000	1195	120
2	Chen Qinglai & Si Chunyuan's Well, Chahaersala Gacha	Chahaertan	105.7216389	39.2826667	1205	120
3	Sumuto No. 3 Well	Chahaertan	105.7157500	39.3006389	1200	120
4	Power Station Pumping Well	Chahaertan	105.7373056	39.3100000	1191	>100
5	Dong Feng No. 2 Well, Chahaersala Gacha	Chahaertan	105.7078333	39.3020556	1193	120
6	Wang Guoyao's Well	Chahaertan	105.7047500	39.2498889	1226	132
7	Water Management Station Well, Nowgan Burga Gacha	Chahaertan	105.7073333	39.2596667	1228	120
8	Shang Yuchang Well, Nowgan Burga Gacha	Chahaertan	105.7043056	39.2817500	1227	110
9	Zi Leishui Well	Chahaertan	105.7188333	39.3204722	1185	105
10	Hu He Xing No. 4 Well	Chahaertan	105.7151944	39.3146667	1191	110
11	Hu He Xing No. 2 Well	Chahaertan	105.7144722	39.3254167	1182	95
12	Wu Da Mu No. 20 Well, Wu Da Mu Tala Gacha	Chahaertan	105.7156111	39.3473611	1175	100
13	Wu Da Mu No. 15 Well	Chahaertan	105.7199722	39.3426667	1168	100
14	Wu Da Mu No. 2 Well	Chahaertan	105.7268056	39.3453333	1169	105
15	Wu Da Mu No. 7 Well	Chahaertan	105.7159167	39.3295278	1187	110
16	Nowgan Tone No. 2 well	Chahaertan	105.7248333	39.3294722	1185	100
17	Yu Chang well, Shilingola Sumu	Chahaertan	105.7267222	39.3600556	1171	60
18	Drinking water well, Little Chahaertan Gacha	Little Chahaertan	105.6464722	39.4705556	1094	>90
19	Fu Qing Dui No. 1 Well, Little Chahaertan Gacha	Little Chahaertan	105.6495000	39.4607500	1096	100
20	Lu Xing Jun Homestay Well	Jilantai	105.6761667	39.6150000	1046	70
21	Salt Mine Factory, Ji Lan Tai	Jilantai	105.7462222	39.7427778	1012	> 50
22	Xilingaole Naoertao Gacha No. 3 Well	Grazing lands	105.7956944	39.3662500	1186	145

Table 6 Selected chemical analysis results for groundwater samples from the Chahaertan aquifer. Full analysis results are presented on the accompanying CD-ROM.

ID	**T ^{o}C**	**SEC** $\mu S\ cm^{-1}$ @ 25 ^{o}C	**DO**	**pH** (pH units)	**Cl**	**SO_4**	**HCO_3**	**NO_3-N**	**Ca**	**K**	**Mg**	**Na**	**Si**	**F**	**Fe**	**Mn**	**Sr**	**Zn**	**As**	**TDS**
1	16.1	822	8.50	7.70	111.0	95.4	139.7	9.76	78.6	2.92	24.6	46.2	6.77	0.2720	< 0.005	0.00015	0.840	0.0068	0.0006	549.3
2	16.5	888	8.31	7.46	127.0	112.0	141.6	7.43	86.8	2.94	24.1	55.7	6.79	0.2300	< 0.005	0.00019	0.847	0.0073	0.0007	590.7
3	15.9	1768	9.39	7.39	192.0	166.0	118.8	71.70	169.0	4.05	48.5	75.8	6.45	0.2110	0.006	0.00029	1.620	0.0097	0.0008	1097.9
4	16.2	679	11.50	7.61	65.1	89.8	147.9	3.57	64.7	2.63	17.9	35.6	6.85	0.2310	0.007	0.00035	0.646	0.0064	0.0006	447.1
5	17.0	893	9.68	7.59	109.0	69.0	125.8	28.90	83.9	3.01	24.2	53.5	6.87	0.2690	< 0.005	0.00037	0.870	0.0070	0.0014	603.6
6	15.9	861	9.85	7.55	121.0	104.0	129.5	8.47	84.2	3.31	24.0	49.4	6.44	0.2440	0.016	0.00370	0.854	0.0083	0.0010	560.2
7	16.4	840	8.50	7.98	97.7	103.0	139.8	6.58	71.0	2.99	22.5	50.5	6.31	0.3700	0.005	0.00089	0.711	0.0070	0.0011	523.8
8	17.0	823	9.10	7.60	108.0	99.4	131.2	10.20	78.9	3.24	22.7	47.6	6.40	0.2620	< 0.005	0.00033	0.815	0.0073	0.0009	543.4
9	15.7	765	9.18	7.65	107.0	91.9	133.1	9.09	73.9	2.99	22.1	49.7	6.54	0.2270	0.007	0.00099	0.774	0.0080	0.0010	528.2
10	15.8	745	9.49	7.66	102.0	74.8	132	6.55	66.4	2.90	19.8	46.7	6.72	0.2430	0.006	0.00074	0.697	0.0069	0.0011	481.1
11	17.8	1802	6.20	7.65	285.0	218.0	115.4	51.30	184.0	3.98	54.7	91.1	6.47	0.2070	0.012	0.00192	1.760	0.0099	0.0018	1186.4
12	15.2	2800	10.32	7.41	369.0	314.0	102.1	137.00	281.0	5.17	92.1	149	6.28	0.1480	< 0.005	0.00043	2.890	0.0110	0.0023	1924.5
13	15.7	705	11.49	7.69	103.0	83.1	132.4	7.44	67.2	3.03	21.0	51.3	6.60	0.2530	< 0.005	0.00043	0.748	0.0067	0.0012	501.4
14	15.0	1330	8.04	7.63	248.0	154.0	125.6	23.50	150.0	3.39	41.3	68.3	6.33	0.2250	0.008	0.00075	1.420	0.0094	0.0018	902.0
15	16.0	1025	11.75	7.68	168.0	125.0	130.3	19.30	104.0	3.13	31.5	70.5	6.59	0.2370	0.011	0.00054	1.040	0.0083	0.0016	725.2
16	16.3	656	11.30	7.80	90.4	79.2	137.9	4.84	65.9	2.98	19.3	42.4	6.42	0.3050	0.019	0.00107	0.679	0.0067	0.0011	466.8
17	15.7	1274	8.54	7.69	215.0	137.0	117.7	21.00	120.0	3.34	38.2	70.8	6.33	0.2420	0.007	0.00042	1.370	0.0089	0.0017	802.4
18	21.6	527	6.50	8.04	43.8	34.8	138	3.28	23.3	2.50	12.4	51	6.26	0.5960	0.006	0.00057	0.409	< 0.004	0.0024	327.5
19	15.6	462	6.40	8.03	50.5	39.5	134.5	3.87	28.5	2.69	15.4	43.3	6.22	0.5640	0.013	0.00032	0.511	0.0043	0.0016	338.7
20	18.2	606	1.78	8.22	64.9	90.0	124.6	1.71	18.5	2.20	10.7	92.7	5.51	0.5810	< 0.005	0.00014	0.629	< 0.004	0.0033	417.8
21	19.1	662	0.00	8.63	89.9	92.1	123.3	1.16	13.3	3.30	12.5	111	4.03	0.5580	0.140	0.01011	0.614	< 0.004	0.0019	455.9
22	17.4	673	8.34	7.70	100.0	67.9	124.1	5.55	58.4	2.88	23.9	38.8	6.74	0.2810	0.110	0.01214	0.802	0.0092	0.0006	448.4

Appendix 4 Groundwater abstraction calculations

CALCULATION METHODS

Four methods were used to estimate total groundwater abstraction from Chahaertan and Little Chahaertan:

- **Average pumping rate per well multiplied by average length of time each well is pumped over one year for every pumping well.** This is likely to be the least accurate method, because it relies on estimating three separate variables that are likely to vary significantly. Pumping rates and the length of time each well is pumped are likely to vary both for individual wells throughout the year and between different wells, so it is difficult to choose accurate 'average' values. The number of pumping wells is easier to constrain, but still may vary from month to month and year to year.
- **Area irrigated multiplied by average volume of irrigation water applied.** The average volume of irrigation water applied per mu was estimated from a number of different sources, including reports from farmers across the aquifer for different crop types, and previous ALERMP studies (Jerie 2006).
- **Electricity usage multiplied by a factor relating volume of water pumped per kilowatt hour used by the pump.** The electricity usage for each well pump is well constrained, because electricity records for each pump meter in Chahaertan and Little Chahaertan were obtained from the electricity supplier. A factor describing the relationship between the volume of water pumped and the electricity used by the pump was obtained from field investigations during this investigation and from previous studies in Chahaertan by government water resources staff.
- **Electricity usage multiplied by the cost of electricity per kilowatt hour multiplied by the volume of water pumped per unit cost.** The electricity usage is well constrained (se previous bullet point). The cost of electricity per kilowatt hour is accurately constrained because it is quoted by the electricity provider. The volume of water pumped per unit cost was obtained from values quoted by farmers in Chahaertan.

ESTIMATING GROUNDWATER ABSTRACTION FROM CHAHAERTAN

1. Flow rate & pumping time: 70 m3/hour x 2880 hours for 95 wells = 19.2 Mm^3 a^{-1}
2. Area irrigated: mu x 600 m^3 = 16.0 Mm^3 a^{-1}
3. Electricity records: KWH x 1.6 = 16.0 Mm^3 a^{-1}
4. Electricity records: KWH x 0.33 CNY x 0.2 m^3 = 16.3 Mm^3 a^{-1}

Approximate total groundwater abstraction = 16 Mm^3 **a^{-1}**

ESTIMATING GROUNDWATER ABSTRACTION FROM LITTLE CHAHAERTAN

1. Electricity records: KWH x 1.6 = 2.5 Mm^3 a^{-1}
2. Electricity records: KWH x 0.33 CNY x 0.2 m3 =2.8 Mm^3 a^{-1}
3. Area irrigated: mu x 600 m3 = 5.3 Mm^3 a^{-1}
4. Flow rate & pumping time: 70 m3/hour x 2880 hours for 49 wells = 9.8 Mm^3 a^{-1}

Approximate total groundwater abstraction = 2.5 – 5 Mm^3/year

Appendix 5 Groundwater modelling: technical details, development and detailed outputs

INTRODUCTION

The groundwater recharge and flow modelling described here was undertaken to aid the understanding of the groundwater system in and around the Chahaertan oases. A steady state groundwater recharge and flow model was developed and refined to create a representation of the groundwater system under long term average climatic conditions and current groundwater abstraction. A dynamic balance groundwater flow model was created to simulate seasonal groundwater level variations under average climatic and current groundwater abstraction conditions, and to further test the steady state model representation. The flow models allowed the recharge model and a water balance for the groundwater system to be tested and constrained.

The model used is ZOOM, which is a collection of object-oriented groundwater models. The object-oriented approach has been adopted to facilitate local grid refinement, which allows groundwater flow to be modelled at different scales using any number of grids placed within each other. The current suite of models includes a distributed recharge model, ZOODRM (Mansour and Hughes, 2004) and a groundwater flow model, ZOOMQ3D (Jackson and Spink, 2004).

CALIBRATION DATA

Any model must be calibrated against real-world data, and the availability and quality of these data is the main control on the degree of model refinement that is possible and the reliability of the final model. The few available calibration data for Chahaertan are:

- Groundwater levels:
  - detailed time series of groundwater level data for six monitoring wells in Chahaertan from 1984 to 1994 (Section 4.4);
  - basic groundwater level data for a number of production wells in Chahaertan and Little Chahaertan, which are usually anecdotal and for unknown dates (see Chahaertan_2006_Well_Survey.xls on attached CD);
  - available groundwater level data for elsewhere in the Quaternary aquifer are rare and comprise only a single value for a well in the southeast of the aquifer near the Helan Mountains (at 105° 52’ 48” east, 39° 6’ 33” north) and an artesian well between Chahaertan and Jilantai (at 105° 40’ 37” east, 39° 37’ 0” north).
- River flow:
  - anecdotal data on the magnitude and duration of river flows at Chahaertan (Section 3.3);
  - limited and qualitative observations of river channel characteristics in the Helan Mountains and over the Chahaertan aquifer (Section 3.3);
  - an empirical estimate of river flows based on the Manning equation for open channel flow (Section 3.3) – 20 to 30 m^3 sec^{-1}.
- Groundwater discharge:
  - Estimate of evaporation from Jilantai lake (Section 4.6.1) – 120 Mm^3 a^{-1}.

MODEL CONSTRUCTION

Boundaries and their justification

The model boundaries are defined, where possible, by physical features of the system. Model boundaries are ideally chosen to be far from the main area of interest, so that they will have little impact on the model simulations. However, the location of the Chahaertan oases is very close to a physical boundary – the western edge of the Quaternary aquifer basin against upfaulted Tertiary rocks – and so in this case the model boundary could not be moved further.

Two model boundaries have been used: one for the recharge model and one for the groundwater flow model (Figure 26).

The recharge model boundary is the larger, and covers the whole of the surface water catchment including the northwestern flank of the Helan Mountains, which receives the highest rainfall of the catchment. Runoff from the mountains is an important component of recharge to the Quaternary aquifer. The boundary is therefore everywhere a catchment boundary.

The groundwater flow model boundary covers the outcrop of the Quaternary aquifer within the catchment area. To the southeast, south and most of the west of the model, the boundary is the contact between the Quaternary aquifer basin and the adjoining Tertiary rocks. To the east, north and northwest, the boundary is the catchment boundary and, in the north, Jilantai lake which is the main natural groundwater discharge point for the drainage system. All the boundaries are represented as no-flow, with the exception of parts of Jilantai lake, which are represented as leakage nodes.

Layering

The groundwater system is modelled as a single layer. Although the Quaternary sediments vary with depth in the aquifer, there are no persistent low permeability layers preventing downward groundwater flow (Section 3.4), and therefore the deposits are likely to act as a single aquifer layer.

Rivers and lakes

The model represents the main river system flowing across the aquifer. River water can infiltrate into the aquifer through the river bed. Because the groundwater level in the aquifer is below river level almost everywhere (groundwater level may lie above river level close to Jilantai, but there are no available data to confirm this), groundwater does not discharge to rivers. The rivers are therefore only represented in the recharge model, as there is no known interaction between saturated groundwater flow and rivers.

The model represents the lake at Jilantai by means of leakage nodes, which allow groundwater to discharge from or to recharge to the aquifer depending on the groundwater head. Because the modelled groundwater head is always above the lake level (as the true groundwater level is), groundwater always discharges to the lake in the model. The lake is the only natural discharge point for groundwater in the model.

Grid

The base grid for both recharge and flow model has a 1000 m square mesh, and is illustrated in Figure 26.

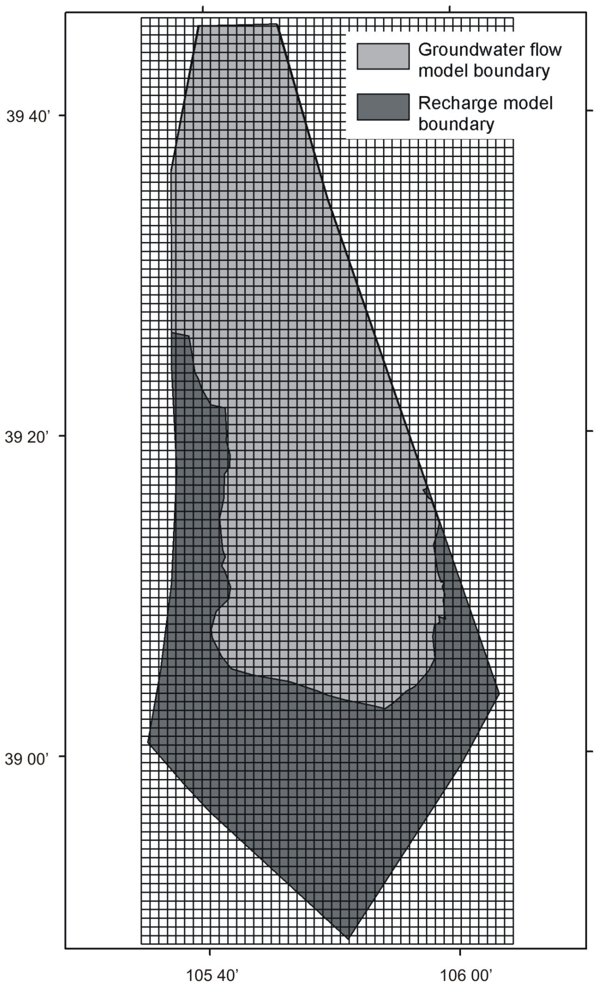


Figure 26 Recharge and groundwater flow model boundaries and model grid

RECHARGE MODEL

Introduction

The recharge model represents the recharge processes as described in Section 4.3. The model calculates distributed recharge over the aquifer to represent spatial and seasonal variation in recharge. It uses a wetting threshold method to calculate direct recharge from rainfall, which is more appropriate for arid and semi-arid regions than the soil moisture balance method that is conventionally used for humid regions. In the wetting threshold method, effective precipitation is first calculated as the difference between rainfall and potential evaporation. If effective precipitation is greater than a wetting threshold – defined as the maximum amount of water that will be absorbed by the soil before any runoff is generated – then the remainder of the effective precipitation over and above the wetting threshold is available for runoff and recharge. A proportion of the remainder is partitioned off to become runoff, controlled by a runoff coefficient, which varies according to slope steepness and the permeability of the underlying geological unit. Runoff is routed downhill to adjacent model nodes, where it may become available again for recharge. Any runoff that does not become recharge is eventually routed to the nearest river node. What is left after runoff is partitioned becomes recharge.

As well as direct recharge, the model also calculates infiltration through river beds and recharge from irrigation returns, where appropriate. Infiltration through river beds is controlled by a river loss coefficient, which varies according to the permeability of the geological unit over which the river is flowing. In irrigated areas, a proportion of the applied water representing the transmission losses is first partitioned off to become recharge. The remaining water is split into two parts: the first becomes runoff which is routed as above; and a soil moisture balance method is applied to the second part to calculate the amount of water that infiltrates to the unsaturated zone and becomes recharge. The relevant model parameters are summarised in Table 7.

A steady state recharge model was developed, simulating recharge over a single year. The recharge model is broadly representative of average conditions over the period 1955 to 1980 (the period for which most climatic data are available), although rainfall data from the period 2003 to 2005 were also used. The use of a steady state model is appropriate as there are not enough data (specifically long term daily rainfall series) to support estimates of transient recharge over more than one year.

Table 7 Recharge model parameters

Parameter	Quaternary aquifer	Tertiary rocks
Wetting threshold	10 mm	3 mm
Runoff coefficient	0.1	0.5
River loss coefficient	0.075	0.01

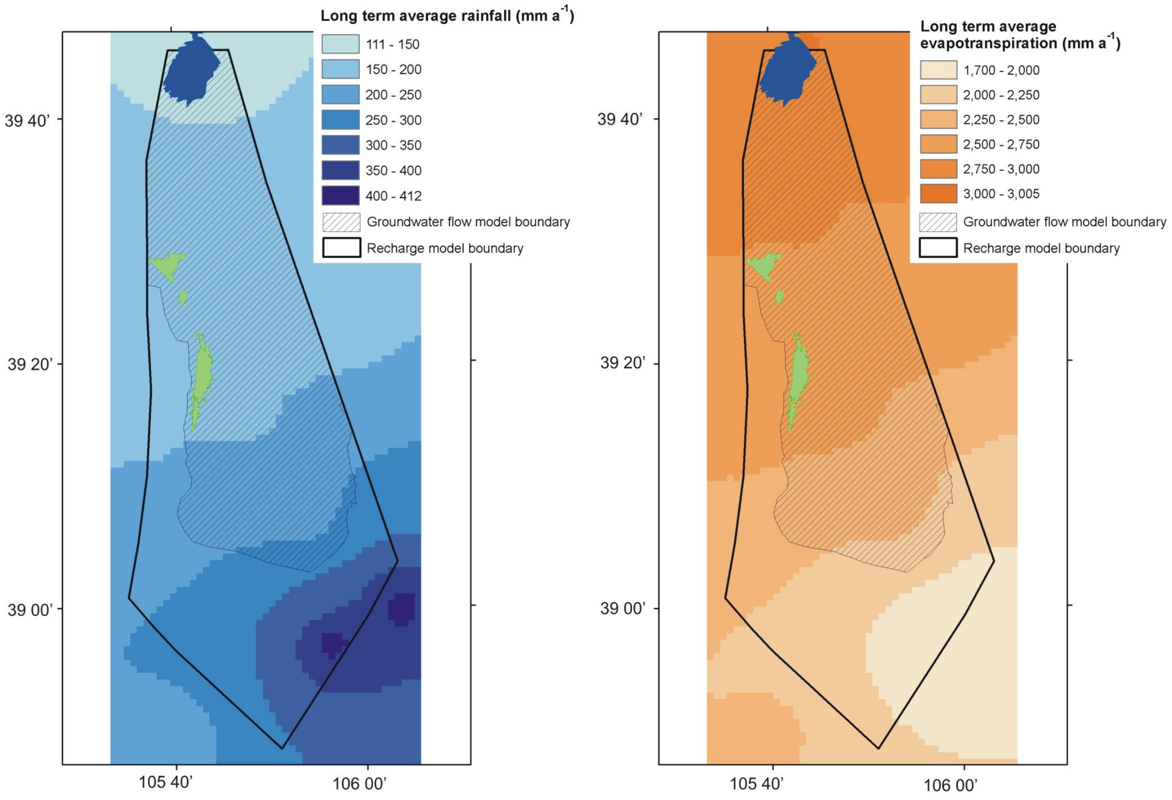
Rainfall and evapotranspiration

To produce a detailed recharge estimation, daily rainfall data are needed. Daily rainfall measurements are made at Bayanhot and Jilantai, but were only available for short periods between 2003 and 2005. A complete year of measured daily data was not available. A limited dataset of daily rainfall for Chahaertan for summer 2006 was also available (Section 3.2 and Appendix 2). In the absence of measured data, a synthetic daily rainfall series for a single year was created for Jilantai, Bayanhot and the Helan Mountains.

The daily rainfall series were created by taking the long term average monthly rainfall at each station and disaggregating each months rainfall into a number of separate rain events, most occurring over a single day but occasionally over two days. The size of each rain event and the number of rain events per month was determined by reference to the available actual daily rainfall measurements and on the total long term average rainfall in each month. For example, at Jilantai measured rainfall events in August varied from 0.5 to 16.2 mm d^{-1} and the long term average August rainfall is 37 mm, or 32% of the long term average annual rainfall of 116 mm. In August 2003 there are data for four rainfall events in Jilantai and in August 2004 for three events. Based on this information, the synthetic daily rainfall series for August for Jilantai has three rainfall events, of 8, 9 and 19 mm d^{-1}, which together add up to 36 mm or 31% of the long term average annual rainfall. For the Helan Mountains, where no daily or long term average monthly rainfall data are available, a synthetic long term average monthly rainfall series was first disaggregated from the available value for long term average annual rainfall, based on the same proportional relationship as the Bayanhot data, and the daily rainfall series then produced as described here. The synthetic daily rainfall series are provided on the accompanying CD-ROM.

Monthly evaporation data are needed for the model, which were available for stations at Bayanhot and Jilantai (Section 3.2 and Appendix 2). These series are also provided on the accompanying CD-ROM.

The recharge model distributes rainfall and evaporation from the data series at individual points (i.e. at meteorological stations) by reference to standard Theissen polygons and the spatial distribution of long term average rainfall and evapotranspiration. Because long term rainfall and evapotranspiration data are only available for three points in the model area (Jilantai, Bayanhot and the Helan Mountains), a synthetic spatial distribution was produced with rainfall and evapotranspiration varying according to elevation (Figure 27).



(i) (ii)

Figure 27 Spatial distribution of long term average rainfall (i) and evapotranspiration (ii) produced for the recharge model

Recharge model refinement

The recharge model was constrained by the maximum estimated groundwater discharge to Jilantai (Section 4.6.1 and Appendix 4) and by refinement of the groundwater flow model. Recharge must be significantly lower than the maximum estimated evaporation from Jilantai of 120 Mm^3 a^{-1}. In the flow model, for a realistic transmissivity distribution, the recharge volume and distribution needed to reproduce realistic groundwater heads across the aquifer was quite closely defined.

GROUNDWATER FLOW MODEL

Introduction

A steady state groundwater flow model was developed. The use of a steady state model allows rapid assessment of whether the choice of boundary conditions, transmissivity (permeability and aquifer thickness) and other parameters, and the recharge calculated by the recharge model, result in an adequate representation of the groundwater system, in particular the groundwater head distribution. The model used steady state average recharge from the recharge model.

A dynamic balance model was subsequently developed to further test the input parameters, including aquifer storage, and the simulation of typical annual groundwater head variations. The model used monthly varying recharge from the recharge model.

A time variant model was not produced during this study, because there are not sufficient available data to warrant its development. A time variant model needs long term historical data series, including recharge (i.e. requiring long term rainfall and evapotranspiration time series), abstraction and natural groundwater discharge, which are not available for the Chahaertan aquifer.

In this and subsequent sections, the term *groundwater head* is used to mean the groundwater level calculated at a point (i.e. a node) in the model. Since the model is a representation of reality, the modelled groundwater head is unlikely to correspond exactly to the true groundwater level in the aquifer. For the Quaternary aquifer, the modelled groundwater head is an approximation to the water table.

Development of transmissivity distribution

One of the key factors controlling groundwater flow is the distribution of transmissivity in the aquifer. Transmissivity is equivalent to permeability multiplied by aquifer saturated thickness. A map of transmissivity across the aquifer was developed based on available data from reports and hydrogeological maps and an interpretation of the permeability and thickness of the Quaternary deposits. This was translated into the input file for the model. The transmissivity variation was refined during model development, and the final distribution is shown in Figure 28. A key model development was to determine that the available transmissivity values for the northern part of the Quaternary aquifer, including the Chahaertan area (Table 1; Groundwater Development and Utilisation Teaching and Research Office, 1984; Yan and Wu, 1996) are probably lower than the average transmissivity across the area. Available values are between 200 and 510 $m^2\ d^{-1}$, but the final values developed during modelling are between 1000 and 1500 $m^2\ d^{-1}$ depending on aquifer thickness.

Aquifer storage

Aquifer (specific) storage was only used for the dynamic balance model. Storage is not a component of a steady state model. No storage data were available for the Chahaertan aquifer, and a specific yield of 0.1 was used based on data from similar Quaternary aquifers in other areas.

Groundwater abstraction

Groundwater abstraction from the Chahaertan oases was reproduced in detail. A total of 150 production wells at accurate locations were modelled, with a total abstraction of 18.4 $Mm^3\ a^{-1}$ (Appendix 4). For the steady state model, the wells were pumped at the same average rate every day of the year. For the dynamic balance model, the wells were pumped at representative pumping rates that varied from zero during the winter months to 1600 $m^3\ d^{-1}$ in the peak irrigation months of July and August.

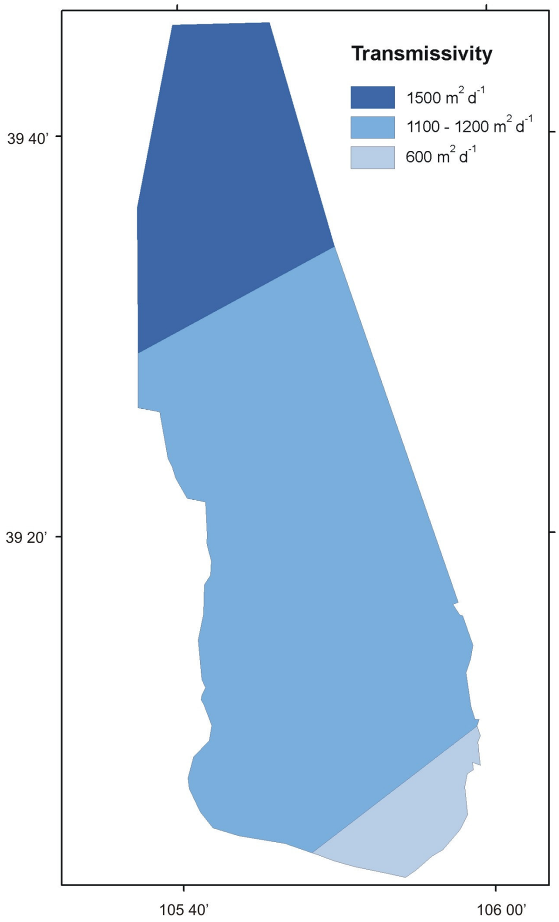


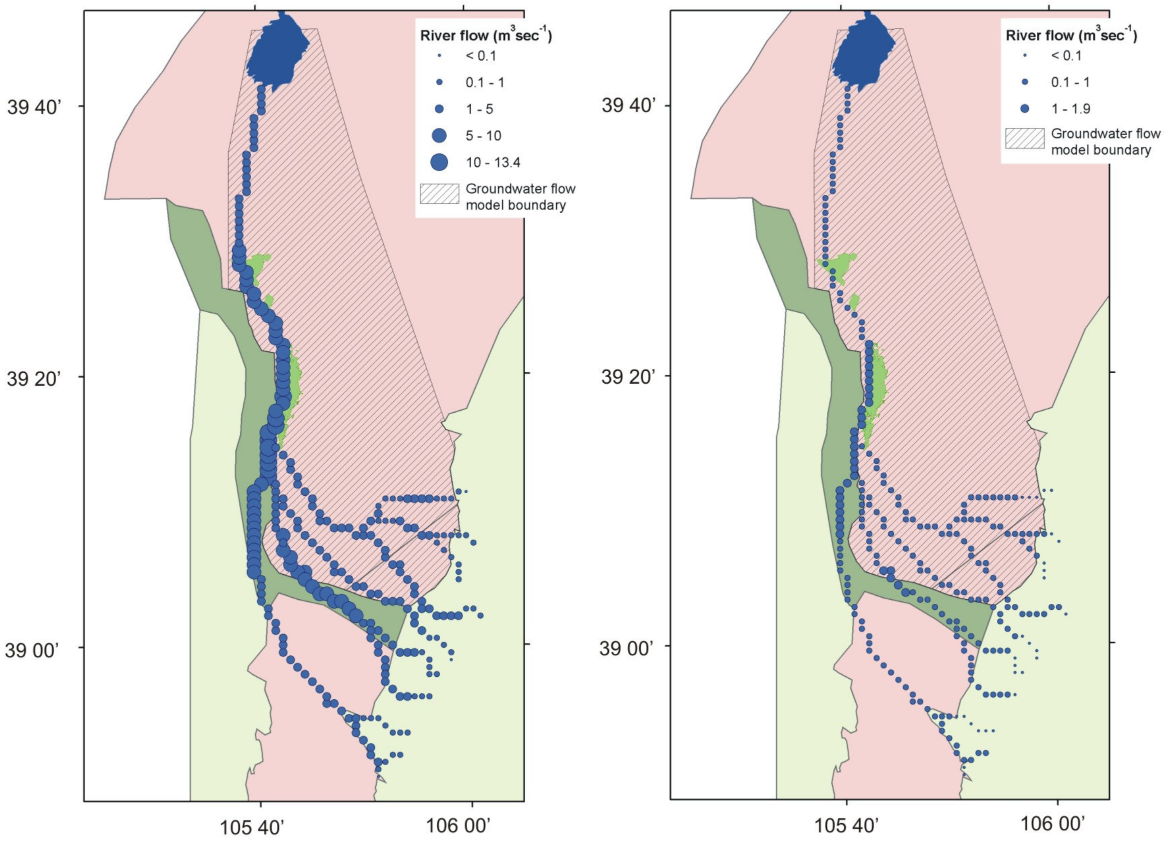
Figure 28 Transmissivity distribution across model. Transmissivity is lowest in the south where the aquifer is thinnest.

RECHARGE MODEL RESULTS

River flow

The river flows reproduced by the recharge model were refined to fit as closely as possible the river flows estimated by the Manning calculation (a target maximum flow of 20 to 30 m^3 sec^{-1}), and the pattern of river flow observed across the aquifer (this section and Section 3.3). The maximum modelled river flow, which occurs following the largest rainfall event (41 mm d^{-1} in the Helan Mountains) is 13.3 m^3 sec^{-1}. This is slightly less than the estimated river flows of 20 to 30 m^3 sec^{-1}, but is well within an order of magnitude and the margin of error in the estimation. Closer refinement of river flows would only be possible if river flow monitoring data were available.

The pattern of modelled river flows shows that little water is lost as the rivers flow over the non-aquifer Tertiary rocks, but that as the rivers flow over the Quaternary aquifer water infiltrates steadily. All the tributaries of the main river system converge just to the south of Chahaertan, so that the largest river flows are seen here and along the edge of the Chahaertan oases (Figure 29).



(i) (ii)

Figure 29 River flows reproduced by the recharge model for (i) a large rainfall event (41 mm d^{-1} in the Helan Mountains) and (ii) a small rainfall event (16 mm d^{-1} in the Helan Mountains).

Recharge

Total modelled long term average recharge to the Chahaertan aquifer is 44 Mm^3 a^{-1}. Of this, nearly half is derived directly from rainfall, almost a third from river leakage and almost a quarter from irrigation returns (Table 8). The spatial distribution of recharge is shown in Figure 30. Recharge across most of the aquifer is low at 15 mm a^{-1}, reflecting the low rainfall and high evapotranspiration. Recharge from irrigation returns in Chahaertan and Little Chahaertan is 350 mm a^{-1}. Recharge from river leakage occurs along the whole length of the modelled river system, varying from 20 mm a^{-1} to 650 mm a^{-1} depending on the maximum river flow in that stretch. The highest river recharge is to the immediate southwest and along the western edge of the Chahaertan oases.

Table 8 Recharge volumes from different sources

Total recharge volume over aquifer (Mm^3 a^{-1})	44
Recharge from river leakage (Mm^3 a^{-1})	14
Recharge from irrigation returns (Mm^3 a^{-1})	10
Direct rainfall recharge (Mm^3 a^{-1})	20

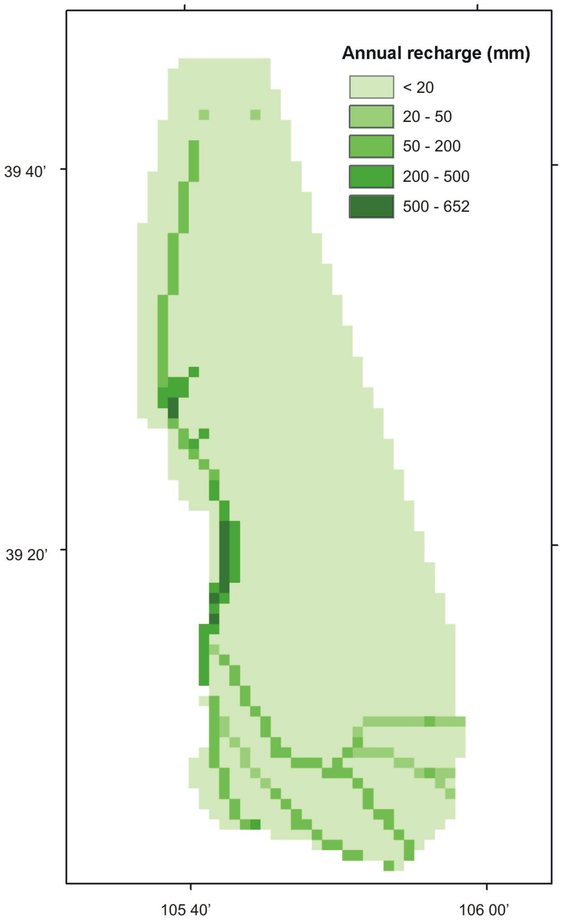


Figure 30 Spatial distribution of modelled recharge across the aquifer

GROUNDWATER FLOW MODEL RESULTS

Steady state groundwater head contours

The steady state groundwater flow model was refined so that the modelled groundwater head distribution fit as closely as possible the available groundwater level data for the aquifer. These data are mainly available in the Chahaertan area, with rare data from elsewhere (see above). Overall the data give a reasonably good fit, to within 10 m in the north of the model and within 15 m at the south of Chahaertan – or within 8 to 12% of the observed head variation across the model (Figure 31). The modelled contours show groundwater flow is dominantly from south to north.

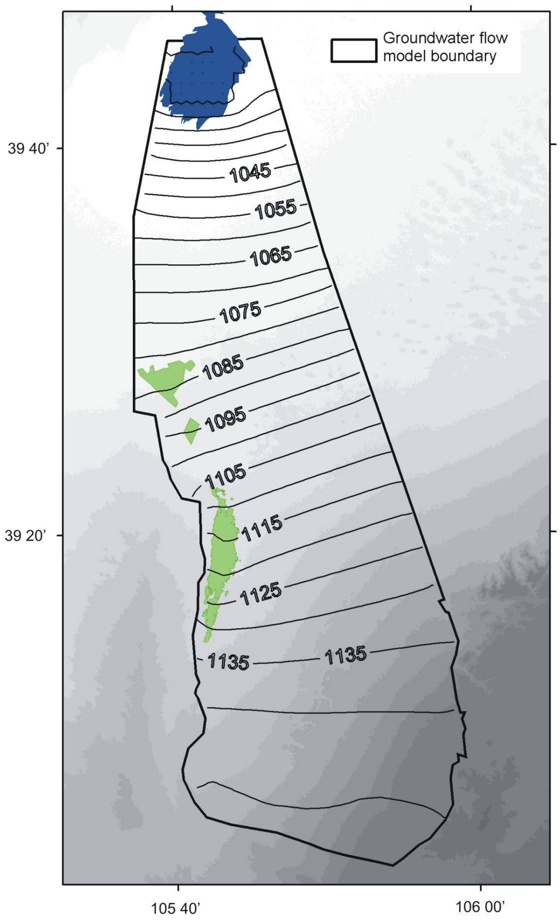
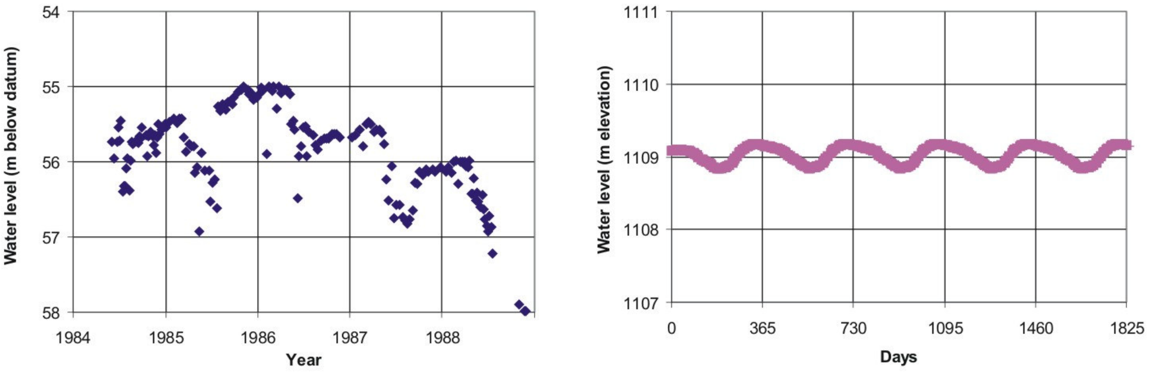


Figure 31 Modelled steady state groundwater head contours

Dynamic balance model

The dynamic balance model produced a relatively good simulation of the typical annual variation in groundwater level in the Chahaertan oasis, with a modelled head variation of 0.3 m per year (Figure 32). This is lower than the average of 1 m per year seen in the Power Station Monitoring Well in Chahaertan (the monitoring well furthest from the main area of abstraction, and therefore least affected by pumping impacts). This is probably partly due to the fact that even the Power Station Monitoring Well is affected by pumping – there is a pumping well within 50 m – so that the annual head variation in the well is likely to be amplified. In the model, the effects of abstraction are averaged over the model grid cells which are 1000 m square, so that the impacts on groundwater head are reduced.



(i) (ii)

Figure 32 (i) Actual groundwater levels at the Power Station Monitoring Well; and (ii) typical groundwater head variation output from dynamic balance groundwater flow model.

Water balance

The steady state water balance is presented in Table 9. All of the inflow (44.26 $Mm^3\ a^{-1}$) derives from recharge, because the model boundaries were no-flow lines. Total modelled abstraction is 18.4 $Mm^3\ a^{-1}$ and total leakage out of the aquifer at Jilantai is 25.81 $Mm^3\ a^{-1}$. The total increase in storage over the aquifer is negligibly small and the global flow imbalance is also small at less than 0.00006 $Mm^3\ a^{-1}$.

Table 9 Summary of steady state water balance

Parameter	**Value**
Total recharge ($Mm^3\ a^{-1}$)	44.26
Total boundary inflow ($Mm^3\ a^{-1}$)	0
Total boundary outflow ($Mm^3\ a^{-1}$)	0
Total abstraction ($Mm^3\ a^{-1}$)	18.40
Total leakage out ($Mm^3\ a^{-1}$)	25.81

Appendix 6 Databases

A number of databases have been set up and populated to hold data collated and collected during this investigation. These are provided on the CD-ROM accompanying this report, and are listed and briefly described here.

- Chahaertan_2006_Well_Survey.xls – production well locations and details collected during a survey as part of this investigation.
- Chahaertan_1992_Well_Survey.xls – production well details (no locations) collected as part of a survey in 1992.
- Chahaertan_Chemistry_Data.xls – chemical analyses of 23 groundwater samples collected from production wells during this investigation, including inorganic major and trace ions, stable isotopes and CFCs.
- Chahaertan_Electricity_Data.xls – electricity usage by production well pumps.
- Chahaertan_Monitoring_Well_Data.xls – groundwater levels measured in monitoring wells in Chahaertan from 1984 – 1994, plus a single measurement in September 2006.
- Chahaertan_Climate_Data.xls – rainfall and evapotranspiration data for the study area from various sources.

Appendix 7 Project workshop presentation

Preliminary results from the groundwater investigation and a discussion of appropriate groundwater investigation techniques were presented at a project workshop on 18 October 2006 in Bayanhot, Alxa League. The workshop was titled ‘Sustainability of Irrigated Oasis Agriculture in Alxa League’. A Powerpoint presentation titled ‘Sustainable groundwater use in Chahaertan oasis’ is provided on the CD-ROM accompanying this report.

Appendix 8 Training course

A two day training course on ‘How to carry out a Groundwater Resource Investigation’ was provided on 23 and 24 October 2006 in Bayanhot, Alxa League. Course notes and a Powerpoint presentation with slides from the course are provided on the CD-ROM accompanying this report. A Powerpoint presentation with preliminary results from the Chahaertan groundwater investigation (in more detail than given in the workshop presentation – see Appendix 3) is also provided on the accompanying CD-ROM.

The course participants are listed here:

Mr Wang Guojing, Left Banner Yellow River Soil and Water Conservation Station

Ms Zhang Silian, Alxa League Meteorology Bureau

Ms Liu Dongmei, Left Banner Well Management Station

Ms Qi Yuezi, Alxa League Water Design Institute

Shi Liang, Left Banner ALERMP Project Management Office

Yang Yuzhen, Alxa League Water Survey Institute

Zhu Jiutao, Bayanhot Hydrology and Water Resource Survey Bureau

Mu Laiwang, Bayanhot Hydrology and Water Resource Survey Bureau

Noel Haug, ALERMP

Ellen Chin, ALERMP

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