12. Summary, Conclusions and Recommendations

The purpose of this short Chapter is to highlight what has been learned from the recent NORPLAN hydrogeological survey of Faryab Province and to consider the implications for future groundwater supply.

12.1 Recharge

The study has supported the existing idea that rainfall recharges aquifers in the hilly and mountainous zones in the south of the Province. These aquifers in turn provide spring discharge and groundwater baseflow to the main river systems draining north (Almar, Qaysar, Maimana, Shirin Tagab) and east (Chechaktu). The rivers also, of course, carry seasonal fluxes of snowmelt and rainfall.

As these river systems pass from the pre-Neogene rocks in the south, onto the Neogene and Quaternary terrain towards the north, the groundwater levels are relatively deep and the rivers commence infiltration of recharge into the Neogene and Quaternary aquifers (Figure 12.1).

Although groundwater levels become shallower as the terrain falls towards the north, groundwater levels are still typically 15 to 40 m below ground level along much of the Maimana and Shirin Tagab valleys (Figure 6.13). Recharge by infiltration of river water persists along much of the Maimana and Shirin Tagab valleys, as far as Andkhoi. A zone of fresher groundwater thus exists along the river corridors of the main rivers (Figures 8.5 and 8.6).

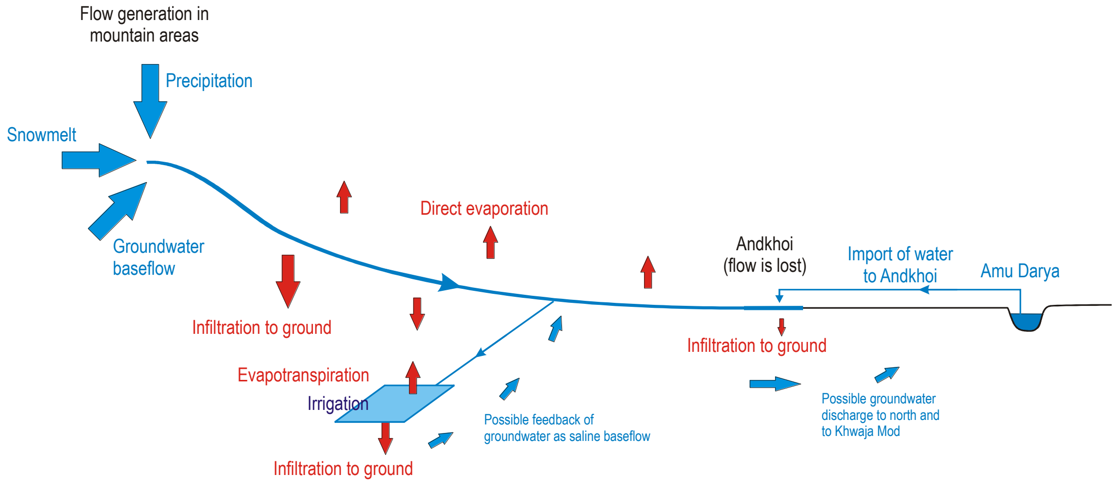


Figure 12.1. Conceptual water balance model for the major rivers of Faryab (e.g. Shirin Tagab)

At specific locations along the main rivers, the water table approaches the surface and limited discharges of groundwater to surface water occur, either as discrete springs (Jar Qala, Ateh Khan Khwaja, Boimoghli - Figure 6.13) or as zones of river flow accretion due to groundwater seepage (Shor Darya, Shirin Tagab north of Araba and around Dowlatabad - Section 6.9). In these latter (groundwater seepage) reaches, river flow typically becomes more saline (due to the influx of more mineralised groundwater) and groundwater resources may also become saline (lack of fresher river water recharge to aquifers).

Direct recharge by infiltration of precipitation

Direct infiltration of precipitation is severely limited over much of Faryab. Based on sparse information regarding potential evapotranspiration and rainfall (Section 2.4), and also upon the relationship between chloride in rainfall and in groundwater, we can make some tentative estimates of the magnitude of direct recharge.

In Maimana, precipitation typically only exceeds potential evapotranspiration in the window December to March (Figure 2.5). In Andkhoi, excess precipitation only marginally occurs in January, implying that opportunities for infiltration of excess rainfall as groundwater recharge will be very limited in the north of the Province.

If there is no anthropogenic or lithological source of chloride (a generally conservative anion) to recent groundwater systems, we can estimate the factor by which chloride is up-concentrated between precipitation and groundwater and, assuming that this up-concentration is due to evapotranspiration of precipitation on vegetation and in the soil zone, we can then estimate the percentage that is evapotranspired and the percentage that is available for recharge.

We already have some real data (Section 2.5) on the concentrations of chloride in rainfall and snowfall: 1-2 mg/L at Andkhoi, 0.1 to 1.7 mg/L at Maimana and c. 0.6 mg/L at Gurziwan. We also have real data for chloride in groundwater near these localities (Figure 12.2). In Table 12.1, a characteristic value towards the lower end of the observed groundwater chloride range is selected, in order to be conservative, as chloride could conceivably have additional sources in evaporite minerals (e.g. in Neogene sediments), in artificial fertilisers or in leachate from latrines in peri-urban areas. There is, however, a risk of being too conservative, however, as low chloride groundwaters could be derived from indirect recharge (infiltration of river water).

	Precipitation	**Groundwater**	**Up-concentration**	**Precipitation**
	mg/L Cl^-	mg/L Cl^-	Factor	mm per annum
Kohistan	Unknown. Say 0.5 mg/L	>1 mg/L	2-4	In some areas > 600 mm
Gurziwan	c. 0.6 mg/L	> 10 mg/L	c. 17	No data. Say 400 mm
Maimana	0.1 - 1.7 mg/L	> 60 mg/L	35 to >100	354 mm
Andkhoi	1 - 2 mg/L	> 300 mg/L	150 to >300	c. 200 mm

Table 12.1. Concentrations of chloride in precipitation (Section 2.5) compared with minimum concentrations of chloride in groundwater (Figure 12.2) and annual quantities of precipitation (see Chapter 2).

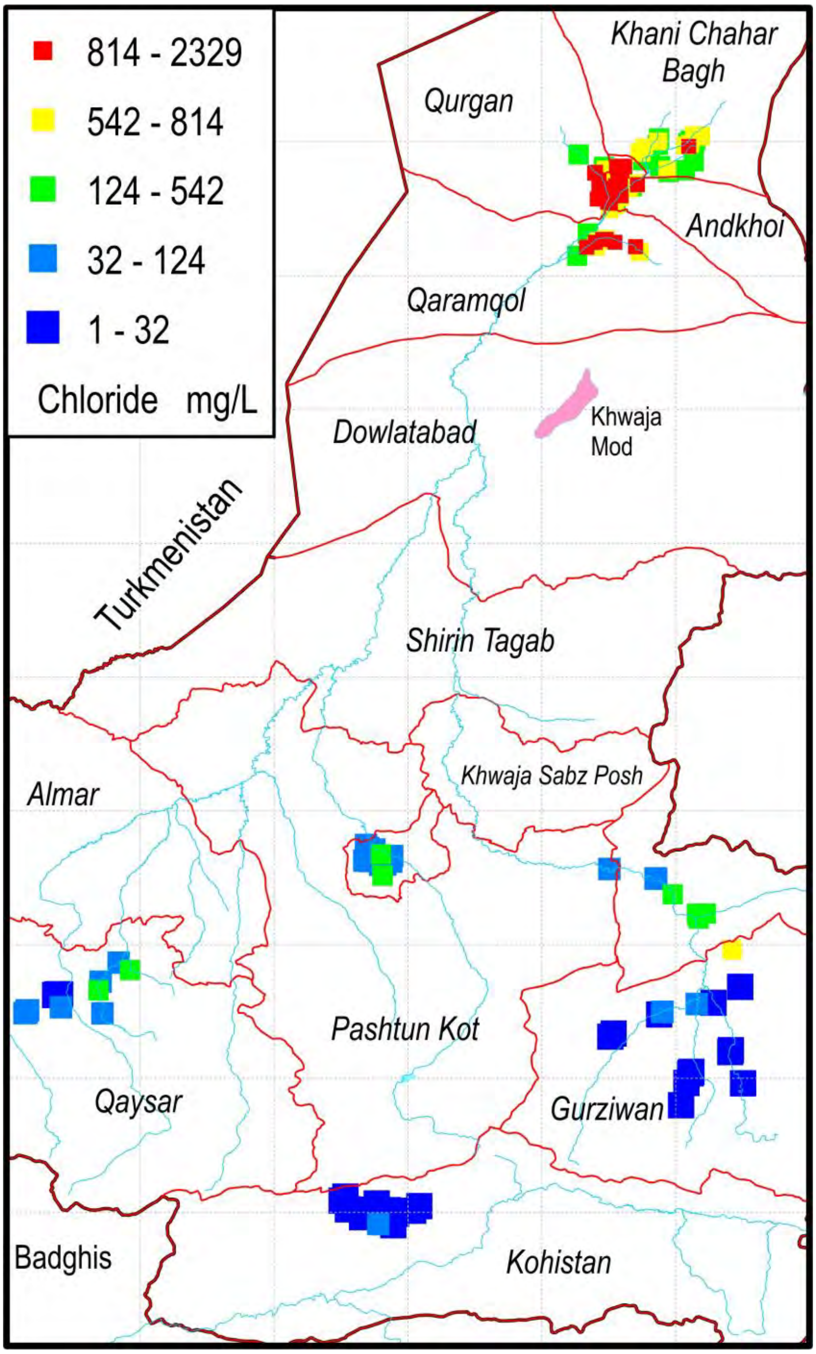
Taking these data at face value, we could thus estimate the direct recharge from precipitation as:

i) Kohistan: 25 to 50% of the precipitation could recharge to permeable subsoil conditions in areas of low topographic gradient: i.e. 150 to 300 mm per year, if the precipitation is 600 mm.

ii) Gurziwan: c. 1/17 or 6% of precipitation could recharge to permeable subsoil conditions in areas of low topographic gradient - around 20 mm/yr.

iii) Maimana: Less than 1/35 or 3% of precipitation could recharge to permeable subsoil conditions in areas of low gradient. Say around 10 mm / year.

iv) Andkhoi: Much less than 1% of precipitation could recharge to permeable subsoil conditions in areas of low gradient - i.e. no more than a few mm of recharge per year and conceivably significantly less.



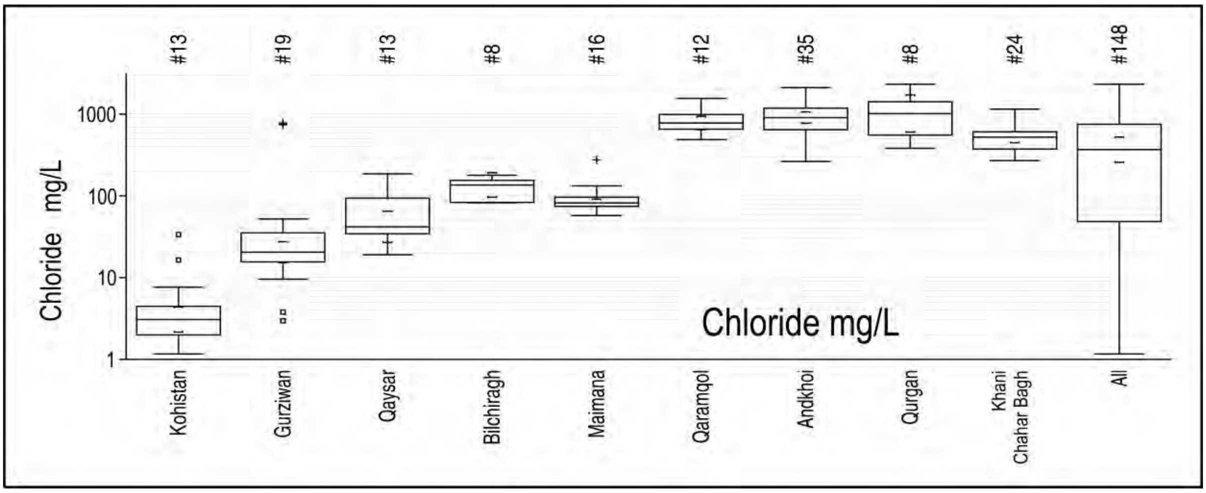
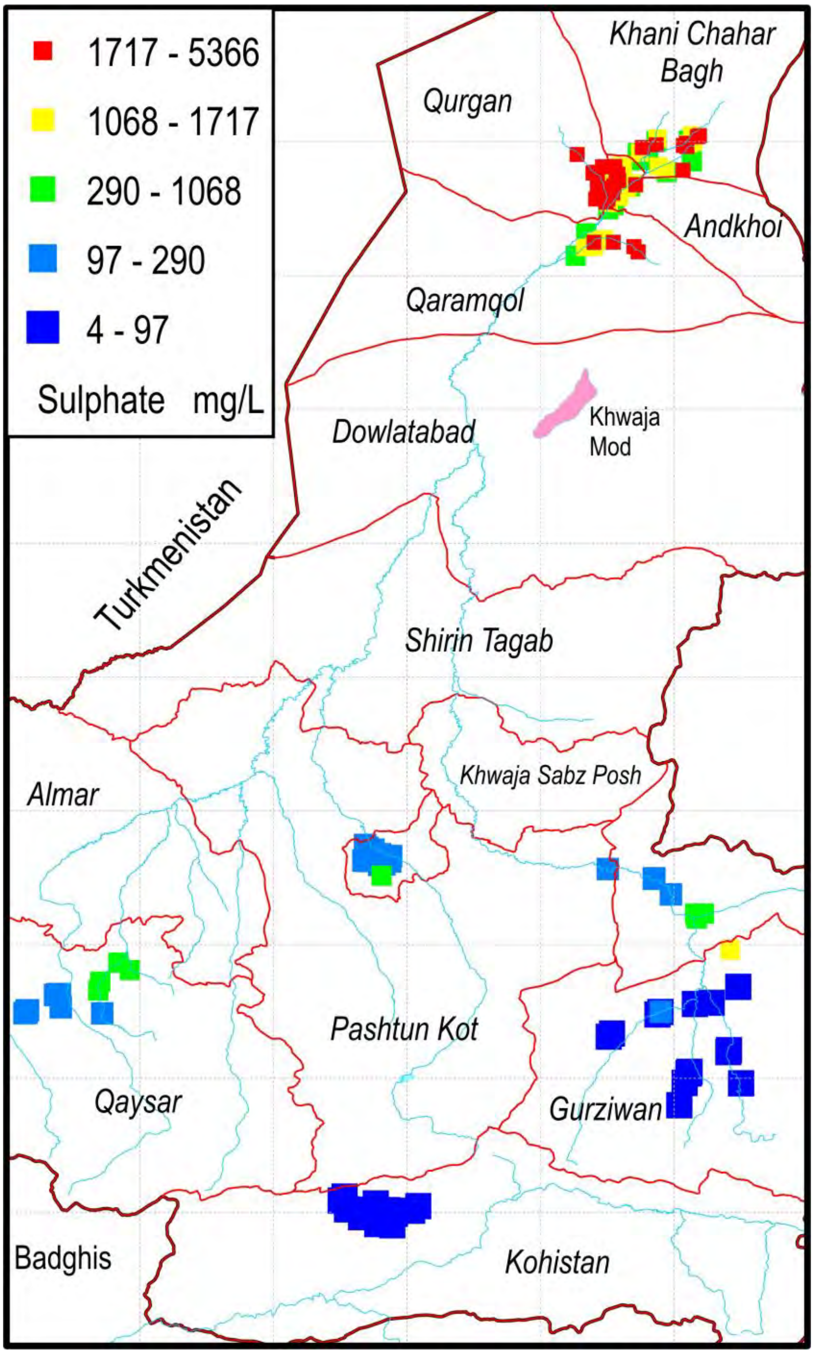


Figure 12.2. Map (top) and boxplots (below) showing concentrations of chloride in groundwater sampled in 2013 and Spring 2014 (N=148). Sub-divisions are based on five equal 20-percentile subsets of the data.



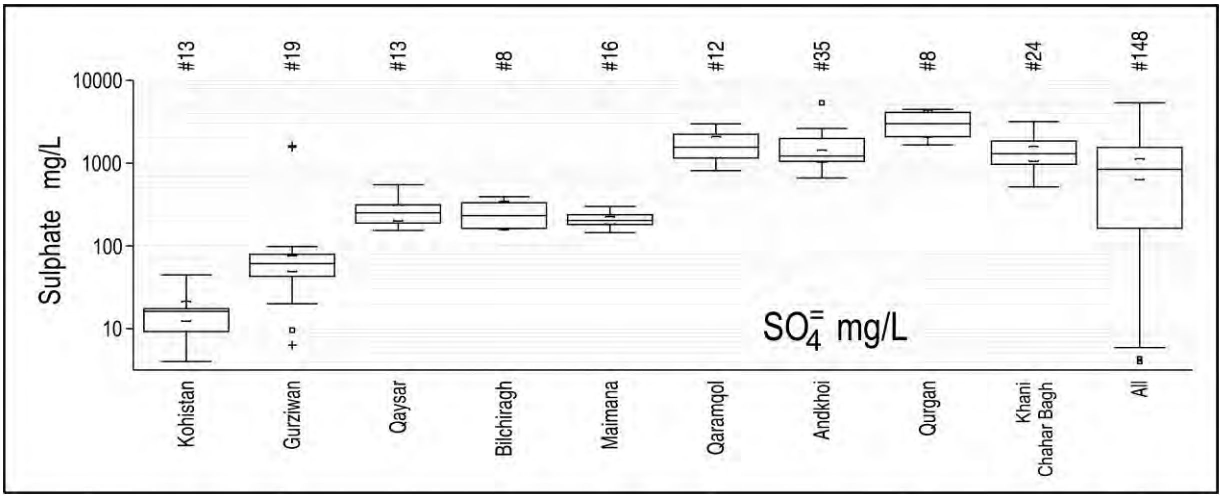


Figure 12.3. Map (top) and boxplots (below) showing concentrations of sulphate (as $SO_4^=$) in groundwater sampled in 2013 and Spring 2014 (N=148). Sub-divisions are based on five equal 20-percentile subsets of the data

We can, in fact, carry out the same exercise with sulphate as with chloride, although this is likely to be less credible, as sulphate can have a lithological source in:

(a) sulphide oxidation in mountain areas
(b) sulphate (e.g. dissolution) in Neogene, or even some Quaternary, areas.

	Precipitation	Groundwater	Up-concentration
	mg/L $SO_4^=$	mg/L $SO_4^=$	Factor
Kohistan	Unknown	> 4 mg/L	
Gurziwan	c. 0.8 mg/L	> 20 mg/L	c. 25
Maimana	0.6 to 3 mg/L	> 140 mg/L	47 to >100
Andkhoi	4 -7 mg/L	> 700 mg/L	100 to >175

Table 12.2. Concentrations of sulphate in precipitation (Section 2.5) compared with minimum concentrations of sulphate in groundwater (Figure 12.3) and annual quantities of precipitation (see Chapter 2).

The results are broadly comparable to chloride, although the up-concentration factors are generally slightly higher, possibly reflecting lithological sulphate sources.

We can also calculate the areally distributed average long term run-off for the upstream gauging stations on the Murghab, Qaysar, Chechaktu and Shirin Tagab rivers

- Qala-e Niazkhan (Murghab River) - 107 mm/a (Section 3.2)
- Chechaktu (Chechaktu River) - 58 mm/a (Section 3.3)
- Khisht Pul (Shirin Tagab River) - 43 mm/a (Section 3.4)
- Qaysar (Qaysar River) - 40 mm/a (Section 3.5)
- Qaysar (between Qaysar and Pata Baba) - 10 mm/a (Section 3.5)

These figures probably slightly overestimate the groundwater baseflow contribution, as they are averages and include episodes of snowmelt and rainfall runoff. However, they lend credence to our estimates of potential direct recharge maybe in excess of 100 mm/a in mountainous areas, a few tens of mm/a in foothill areas, to <10 mm in the Neogene / Quaternary portions of Faryab.

Indirect Recharge

The magnitude of river water infiltration to Neogene and Quaternary aquifers has proven impossible to quantify, as the major component of the rivers' water balance (offtake for irrigation) is not systematically recorded or licensed.

We observe, however, that the salinity of the rivers typically increases downstream roughly in proportion to decrease in flow.

- If all the flow loss were by infiltration to the ground - one would not expect to see an increase in salinity.
- If all the flow loss were by evaporative processes - one would expect to see an almost perfect inverse relationship between salinity and flow.

The documented relationship between salinity and flow approaches inverse proportionality. The stable isotope patterns also strongly indicate evaporative processes. Thus, we conclude that

1. **the main mechanism for flow loss from rivers in the central and northern parts of Faryab is by evapotranspiration.**

The length and area of the rivers are insufficient for this evaporation to be taking place by direct evaporation from the rivers' open surface. Thus, given that the major abstractions from the rivers are for irrigation use, we strongly suspect that

2. **the main mechanism for flow loss from rivers in the central and northern parts of Faryab is by evapotranspiration of river water abstracted and used for irrigation processes.**

The corollary of this is that

3. **the main mechanism for salt accumulation in both rivers and groundwater in the central and northern parts of Faryab is by evaporative processes - including the evapotranspiration of water used for irrigation and the period flushing of evapoconcentrated rainfall-borne and windblown salts from the soil zone.**

We fully acknowledge that other processes may be important, including dissolution of palaeoevaporite salts, such as halite or gypsum, from Neogene and other deposits.

This implies that the quantity of recharge available from river infiltration to aquifers is limited. The reason for this may be related to the fact that, in the vicinity of the main rivers, the uppermost few metres of the sedimentary sequence often seem to comprise low permeability clays and silts, which would hinder infiltration. The limited quantity of infiltration is also evidenced by:

a) the narrowness of the fresh groundwater zones along the main rivers (see, e.g., Figures 8.5 and 8.6).

b) the hydraulic disconnect between groundwater levels and river levels along most of the main river valleys (see Sections 6.5 and 6.6).

12.2 Water Resources and Water Supply

There is a pressing need for improved access to potable water in many areas of Faryab. In rural areas, the practice of using narrow-diameter boreholes (4" casing - too narrow to allow installation of large motorised pumps), fitted with handpumps, appears to be an appropriate response, and is designed to limit the abstraction density of groundwater.

In urban and peri-urban areas, such as Maimana, the density of demand is higher. In Chapter 6, we have seen that there appears to be a significant aquifer resource in the vicinity, and to the west and south of, Maimana Airport (Section 6.5). However, we have noted that the recharge mechanisms to this aquifer are not yet adequately quantified. Direct recharge is likely to be very limited (a) due to the high evapotranspiration and (b) due to the generally low permeability clay-silty layer in the immediate subsurface. Indirect recharge from the Maimana River probably takes place, but is likely to be limited by low-permeability clayey strata hindering hydraulic continuity with the aquifer.

It is clearly tempting to sink deep, wide diameter boreholes into the aquifer strata in the vicinity of the city to provide a solution to Maimana's water supply - and indeed this *may* be plausible and sustainable. However, although the existence of a groundwater storage has been proved, the existence of a **sustainable water resource** has neither been proved nor quantified. In order to do this, the mechanisms of recharge need to be clearly understood and quantified, and a numerical model of the aquifer should ideally be constructed to assess what proportion of the available groundwater recharge should be abstracted. The consequences of over-abstraction can be two-fold:

i) Local. Intensive abstraction from a deep borehole will cause local lowering of the water table (according to variations on Theis's (1935) algorithm), possibly causing drying-up of shallower (dug) wells.

ii) Regional. If abstraction significantly exceeds recharge, the water table across the entire aquifer could be affected, resulting in a year-on-year decline. Such a situation can take many years to reverse.

12.3 Water Supply to Andkhoi

The current hydrogeological survey has not yet found any evidence of fresh, potable groundwater reserves in the vicinity of Andkhoi (Section 6.7). Indeed, the least saline groundwater reserves of the Andkhoi area have an electrical conductivity of more than 2000 µS/cm (and usually significantly more), with a mode / median of around 5000 µS/cm. Just a handful of groundwater sources return conductivities in the range c. 1500 - 2000 µS/cm (Figure 8.2). An electrical conductivity in the range 2000-3000 µS/cm is normally considered on the limits of what is acceptable for human consumption (approximately representing a mineralization of 1.6 to 2.4 g/L (see Section 8.7).

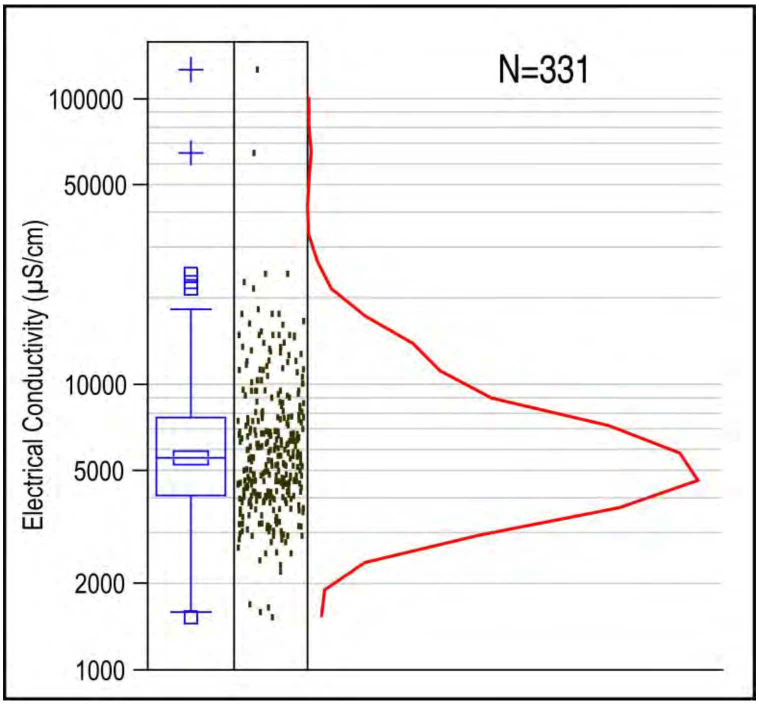


Figure 12.4 Combined boxplot, scatterplot and density plot showing the distribution of the 331 electrical conductivity measurements registered in the NORPLAN database (as of Summer 2014) for the four northern districts of Khani Chahar Bagh, Qaramqol, Qurgan and Andkhoi.

Thus, in summary, good potable groundwater supplies are extremely rare in the Andkhoi area. Prevailing hydrogeological wisdom suggests that the few fresher groundwaters are typically found near flowing irrigation canals and/or at a modest depth (below an upper shallow horizon of saline water). It would be very beneficial if this hypothesis could be verified by an empirical scientific study.

Alternative strategies for water supply could include:

Desalination of brackish groundwater by reverse osmosis: The NGO Norwegian Church Aid (NCA) has been running demonstration projects in the Andkhoi region for

several years, which appear to demonstrate that desalination of small quantities of saline groundwater for human consumption can be achieved using reverse osmosis units. The limitations on the further development of this as a water supply strategy are:

- Only rather modest quantities of a few litres per person per day can realistically be achieved.
- The reverse osmosis technology employed depends on a reliable source of affordable electrical power being available (which may be mitigated in the Andkhoi region by the availability of mains electricity imported from Turkmenistan).
- The limited availability and affordability of spare parts and consumables.
- The limited availability and affordability of technical expertise to maintain such systems.

Desalination of brackish groundwater by solar distillation: There appears to be some scope for the desalination of brackish groundwater by solar distillation in the area, but this needs to be verified by further field trials. This option removes many of the limitations related to cost, electricity supply, spare parts and technical expertise. The limitations of this technology are:

- It still also only provides a few litres of fresh water per person per day.
- Overcast weather may also reduce the quantities of water that can be produced.

Blending of distilled water with equal quantities of safe brackish groundwater would increase the available yields.

Long-distance import of fresh water: Given the lack of fresh groundwater reserves in the vicinity of Andkhoi, and given the paucity of fresh groundwater reserves in the Quaternary and Neogene aquifers in the centre and north of Faryab Province, the most promising large-scale source of uncommitted fresh groundwater is the river bank aquifer deposits of the Amu Darya. Indeed, in Chapter 1, we noted that a major engineering project was recently contracted by the Government for the construction of a pipeline to carry fresh groundwater to the Andkhoi region from a well-field on the southern bank of the Amu Darya river near Kelif (MUMTAZ 2007).

This project appears to have been unsuccessful, reportedly due to engineering issues with the pipeline construction and materials. We note, however, that the large scale importation of fresh water to a desert city such as Andkhoi would potentially increase infiltration of waste water to the ground, via pit latrines, pipe leakages and irrigation. Increased infiltration of waste water *could* lead to a modest rise in water table and a freshening of the groundwater resource. However, it *could* also lead to waterlogging problems if the water table rise was excessive and *could* lead to salinisation of groundwater, depending on the salt content of the existing unsaturated zone. Such a scenario is recorded from many areas of the world where water has been imported to arid city environments, most notably in Riyadh, Saudi Arabia (Kreibich & Thieken 2008).

12.4 Thermogeology

The global scientific and engineering community is gradually coming to realise that the subsurface environment is potentially not just a source of one of humankind's most fundamental needs - potable water - but also of a second - heating and cooling.

In Chapter 7, we saw that the shallow ground and groundwater in Faryab is of such a temperature that it could be used for:

- space cooling (air conditioning) of buildings, via the use of a ground source heat pump.
- space cooling (air conditioning) by direct passive application (of cool groundwater) in the southern mountainous districts where the ground temperature is <12°C.
- space heating of buildings during winter, via the use of a ground source heat pump

Such ground source heating and cooling is facilitated by the availability of groundwater (so-called "open-loop" systems), but can also operate by sinking subsurface heat exchangers in boreholes where ground water is absent ("closed loop" systems - Banks 2012). Where groundwater is present, its quality is of little importance: thus, contaminated or saline groundwater could be used for heating and cooling purposes, even if it is not suitable for potable or irrigation purposes.

12.5 A Future Research Strategy

To make progress in the issues outlined above, we suggest the following recommendations for a national strategy for hydrogeological research. Many of the issues are not specific to Faryab, but apply equally well to other Provinces where groundwater resources are marginal and salinisation is a potential problem (e.g. most of the northern region - Jawzjan, Badghis, Balkh) and many provinces in the south and west of the country.

<u>Quantification of Direct Recharge to Groundwater</u>

Quantification of the rate of recharge of groundwater resources in Afghanistan is a key issue. To make real progress in this issue, the following are recommended:

- to continue to improve the national network of meteorological monitoring stations.
- of particular importance is the free availability of **daily data on rainfall/snowfall and potential evapotranspiration** from selected key meteorological stations (e.g. Maimana).
- such daily data can be incorporated into a **Penman-Grindley type recharge model** (Hiscock & Bense 2014), applying root constants for known vegetation coverage, to estimate daily soil moisture deficits and potential recharge.
- the results of such modelling should be backed up by empirical determination of soil moisture content and deficit at key meteorological stations.
- the recharge estimates should be verified by examining hydrographs from the national network of observation wells. This network should include boreholes away from the main river courses, such that direct recharge, unaffected by possible river infiltration or loading interference, can be estimated.
- the major anion (especially **chloride**), cation and stable isotope contents of rainfall / snowfall should be regularly analysed at an accredited laboratory (with appropriately low detection limits), from key meteorological stations on a regular basis.

Quantification of Indirect Recharge from Rivers to Groundwater

This topic is very site-specific. We would recommend continuing with the work that NORPLAN has commenced at study sites (see Chapter 6):

- adjacent to the Maimana River near Maimana Airport (Section 6.5)
- adjacent to the Shirin Tagab river near Islam Qala (Section 6.6)

Plans for proposed field activities are outlined in NORPLAN (2014: Part 2). In essence, these plans should encompass:

- Geophysical profiles perpendicular (and along) the river, to ascertain how the nature of the aquifer (electrical resistivity) changes with distance from the river, and where the base of the aquifer is located.
- A profile of wells perpendicular to the river, to verify how the aquifer stratigraphy changes with distance from the river. These wells should be sampled for groundwater chemistry and stable isotopes (and, in the future, possibly also ^{14}C, chlorinated fluorocarbons (CFC), sulphur hexafluoride (SF_6) and other indicators of groundwater age).
- One or more of the drilled wells in the vicinity of the river should be constructed as a test production well and subjected to long-term constant-rate test pumping. During the test pumping:
  - water levels in the production well and surrounding monitoring wells should be continuously recorded.
  - water levels in the river should be continuously recorded.
  - the production well should be regularly sampled for chemistry, stable isotopes and any other indicators of riverine influence.
  - recovery of water levels following test pumping should also be recorded.
- Analysis of the test pumping results should permit some assessment of the degree of hydraulic continuity with the river.
- Coring or other sampling of any silty/clayey sediments (a) in the uppermost portion of borehole profiles and (b) in boreholes in the proximity of the river, should be supervised by a sedimentologist, who can identify the petrogenesis of the sediments and can assist in constructing a sedimentological model of the aquifer system.
- Sediments in the bed of the river should, if possible, be cored and samples assessed for their likely hydraulic conductivity.
- At least one observation well (and preferably more) should be regularly or continuously monitored in the long term.
- The collected information should be collated into a numerical model of the aquifer-river system, with well-considered boundary conditions. This model can be continuously updated with new information and can be used to test out hypotheses, aquifer conceptualisations and the potential impacts of new abstractions.

Catchment Water Balance

The key missing component in catchment water balances in the Faryab area has been offtake for irrigation.

Future water balance studies should focus on

- Quantifying irrigation off-takes from the Maimana and Shirin Tagab Rivers.
- Auditing the areas of land and crops served by each offtake.
- Making some assessment of evapotranspiration, drainage and infiltration losses from irrigated land.

Fresh Groundwater Resources near Andkhoi

At a limited number of localities (say, 3-4), both away from and in the vicinity of flowing irrigation canals, deep boreholes should be constructed with a view to ascertaining changes in pore water salinity with depth.

This could be achieved by conventional progressive coring techniques, followed by extraction of pore waters and analysis for major ion chemistry and stable isotopes.

Alternatively, conventional percussion drilling could be employed. Here, a string of plain steel casing would be progressively advanced in (say) 5 metre intervals. Each drilling interval would be followed by a period of resting, purging and sampling the groundwater at the base of the casing. In such a way, a depth profile of groundwater quality could be built up.

Khani Chahar Bagh

We note that the northern part of the Andkhoi area (Khani Chahar Bagh) is observed to have:

- somewhat less saline groundwater than Qurgan and Andkhoi districts.
- a somewhat deeper water table than Qurgan and Andkhoi districts.
- a somewhat different chemical signature than Qurgan and Andkhoi districts.

This is unexpected and we feel that an understanding of the reasons for this could shed light on the mechanisms for groundwater occurrence and recharge throughout the entire Andkhoi region.

A specific groundwater research project could potentially be dedicated to an understanding of groundwater occurrence and hydrochemistry in Khani Chahar Bagh, and should probably be coupled to a seasonal hydraulic monitoring and chemical sampling of the main irrigation canals in the area.

Import of Fresh Water to Andkhoi

We believe that a research project examining the hydrogeological implications of the import of fresh water to the Andkhoi area would be highly valuable. Components of this research should include:

- Quantification of the likely imported water flux and its distribution within the Andkhoi area.
- Assessment of the likely usage (household washing and sanitation, dust damping, industrial, irrigation) and quantities / final destination of wastewater generated (infiltration from latrines and soakaways, infiltration from agriculture, evapotranspiration, canalised drainage or sewage).
- Assessment of likely quality of wastewater from different sources.

- Shallow drilling and coring of unsaturated zone to assess leachable saline salt content of unsaturated zone sediments.
- Limited drilling of deeper (c. 100-120 m) observation boreholes to characterise hydrogeological succession at a coarse level of detail. Continued monitoring of these boreholes.
- Overview (i.e. relatively "coarse") numerical model of shallow hydrogeology of Andkhoi, which would permit testing of hydraulic impacts of various infiltration scenarios on groundwater flows and levels.
- Evaluation of impacts of various mitigation strategies, e.g.:
    - canalisation of wastewater / sewage to irrigation canals, with various different levels of treatment.
    - canalisation of wastewater / sewage to evaporation basins, with various different levels of treatment.
    - more local, passive treatment / filtration of wastewaters, followed by re-use as local irrigation water.