Hydrogeology of the Kabul Basin (Afghanistan), part I: aquifers and hydrology

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Abstract Shallow groundwater represents the main source for water supply in Kabul, Afghanistan. Detailed information on the hydrogeology of the Kabul Basin is therefore needed to improve the current supply situation and to develop a sustainable framework for future groundwater use. The basin is situated at the intersection of three major fault systems of partially translational and extensional character. It comprises three interconnected aquifers, 20–70m thick, consisting of coarse sandy to gravely detritus originating from the surrounding mountains. The aquifers were deposited by three rivers flowing through the basin. The coarse aquifer material implies a high permeability. Deeper parts are affected by cementation of pore spaces, resulting in formation of semi-diagenetic conglomerates, causing decreased well yields. Usually the aquifers are covered by low-permeability loess which acts as an important protection layer. The main groundwater recharge occurs after the snowmelt from direct infiltration from the rivers. The steadily rising population is estimated to consume 30–40 million m^3 groundwater per year which is contrasted by an estimated recharge of 20–45 million m^3/a in wet years. The 2000–2005 drought has prevented significant recharge resulting in intense overexploitation indicated by falling groundwater levels.

Keywords Afghanistan · Urban groundwater · Arid regions · Over-abstraction · Unconsolidated sediments

Introduction

Afghanistan was affected by a long period of wars from 1979 to 2002. As a result, much of the country's

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infrastructure, including the water supply in Kabul, has been destroyed. The population sharply increased from 1.8 million in 2002 to an estimated 3.0 million in 2004 due to a vast immigration of former refugees. A severe drought lasting from 1998 to 2004 further complicated Kabul's water problems. Groundwater is the major source for drinking water in the Kabul Basin. Only 20% of the population have access to tap water. The rest depends on shallow wells equipped with hand pumps.

The emerging mega city Kabul desperately needs an adapted water supply concept and water resources management. Reliable hydrogeologic data are an indispensable prerequisite for this. On behalf of the Federal Foreign Office of Germany, the Federal Institute for Geosciences and Natural Resources (BGR) resumed its work in Afghanistan in 2003. Together with Afghan experts, information on the groundwater resources of the Kabul Basin was gathered. The project was focused on the Kabul Basin due to the desperate water-supply situation there. Part I of this study describes the hydrologic and hydrogeologic situation of the Kabul Basin. Since most files in Afghanistan have been lost due to the war most of the data had to be taken from the BGR archives (Homilius 1966; Böckh 1971; Dietmar 1976). BGR almost continuously worked in Afghanistan from the beginning of the 1960s till the dawn of the Soviet invasion in the end of the 1970s. Practically no relevant data were recorded from 1979 to 2001. Data recording recommenced tentatively around 2002 although many river gauges, monitoring wells and rainfall gauges are still not operating due to a lack of equipment, expertise or both. The data sets collected in the last few years are often too short to allow any valid interpretation.
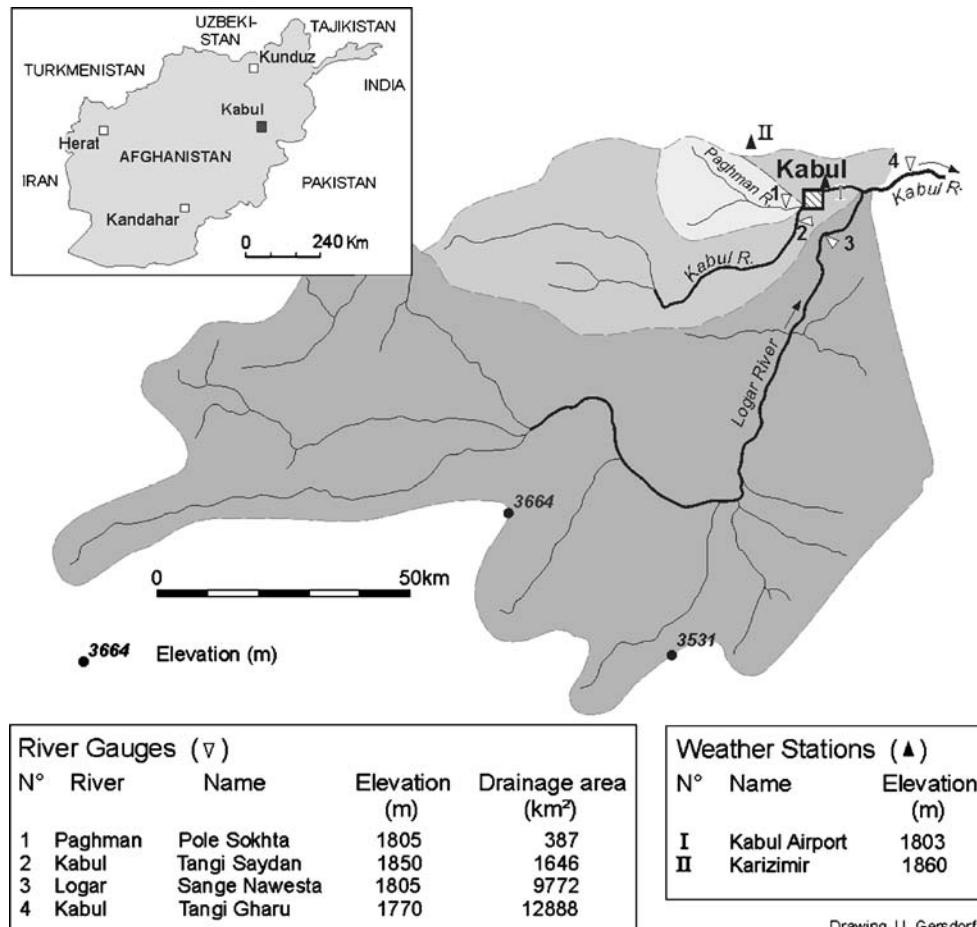
Geology of the Kabul Basin

The Kabul Basin (Figs. 1 and 2) is a basin structure which arose as a result of plate movements during the late Palaeocene (Tertiary). Faults of partially translational and extensional character give evidence of the intensive tectonic stress field, namely the Herat-Bamiyan main fault in the west, the Sorobi fault in the east and the Chaman fault system in the south-east. The basin covers an area of about 1,600 km² and is surrounded and underlain by largely metamorphic rocks. These rocks are part of the Kabul block and are fragmented along the fracture and

Fig. 1 Schematic map of the catchment areas of the rivers of the Kabul Basin and the gauging stations (redrawn after Böckh 1971)

shear paths and intensely folded and even imbricated in parts.

The western and northern rims of the basin are dominated by Precambrian gneisses, mica slates, amphibolites, quartzites and marbles (Homilius 1966). Precambrian phyllites are found in the eastern and southern parts (Dietmar 1976). The carbonate-dominated Khinghil formation of Permo-Triassic age was overthrusted into the south of the recent Kabul Basin. The filling of the Kabul Basin itself consists of younger Tertiary (Neogene) and Quaternary terrestrial and lacustrine sediments (Figs. 3 and 4). Geophysical surveying revealed a total sediment thickness of up to 600 m. The basin sediments can be subdivided as described in the following.

The molasse-type Butkhak series of the upper Miocene consist of different beds of clastic material. It mainly comprises red sandstones, gravels, conglomerates and breccias. They were formed after the early Tertiary Alpidic uplift of the Hindukusch. The Pliocene Kabul series developed in the central part of the Kabul Basin and mainly consist of argillaceous beds, lacustrine silts and fine sand lenses. Greenish colours are common. The boundary between Miocene and Pliocene is not only lithological, but also chronological and marked by a hiatus caused by strong erosion. The Quaternary terrace sedi-

ments of middle and younger Pleistocene age (Lataband formation) form the main aquifers within the Kabul Basin. Deeper parts have often been affected by cementation leading to the genesis of conglomerates.

The youngest formations are loess deposits which reach their highest thicknesses at the rim of the basin. Many loess layers have been reworked one or more times. The oldest loesses are intercalated with the Lataband gravels. In the basin centre, some swamps arose from lakes and depressions without outlet. Intense evaporation led to the concentration of salts in the soil of these evaporation basins.

Aquifers of the Kabul Basin

The major part of the catchment of Kabul River consists of consolidated rocks of the mountains surrounding the city of Kabul (Fig. 1). The city is underlain by three hydraulically interconnected unconsolidated aquifers deposited as river terraces by the rivers Paghman, Logar and Kabul. They comprise only one eighth of the entire catchment area. Due to the short transport distance of the material, the deposits are usually coarse-grained, ill-sorted and often show a distinct heterogeneity. Permeability varies and ranges from 2.3×10^{-5} to 1.3×10^{-3} m/s, the
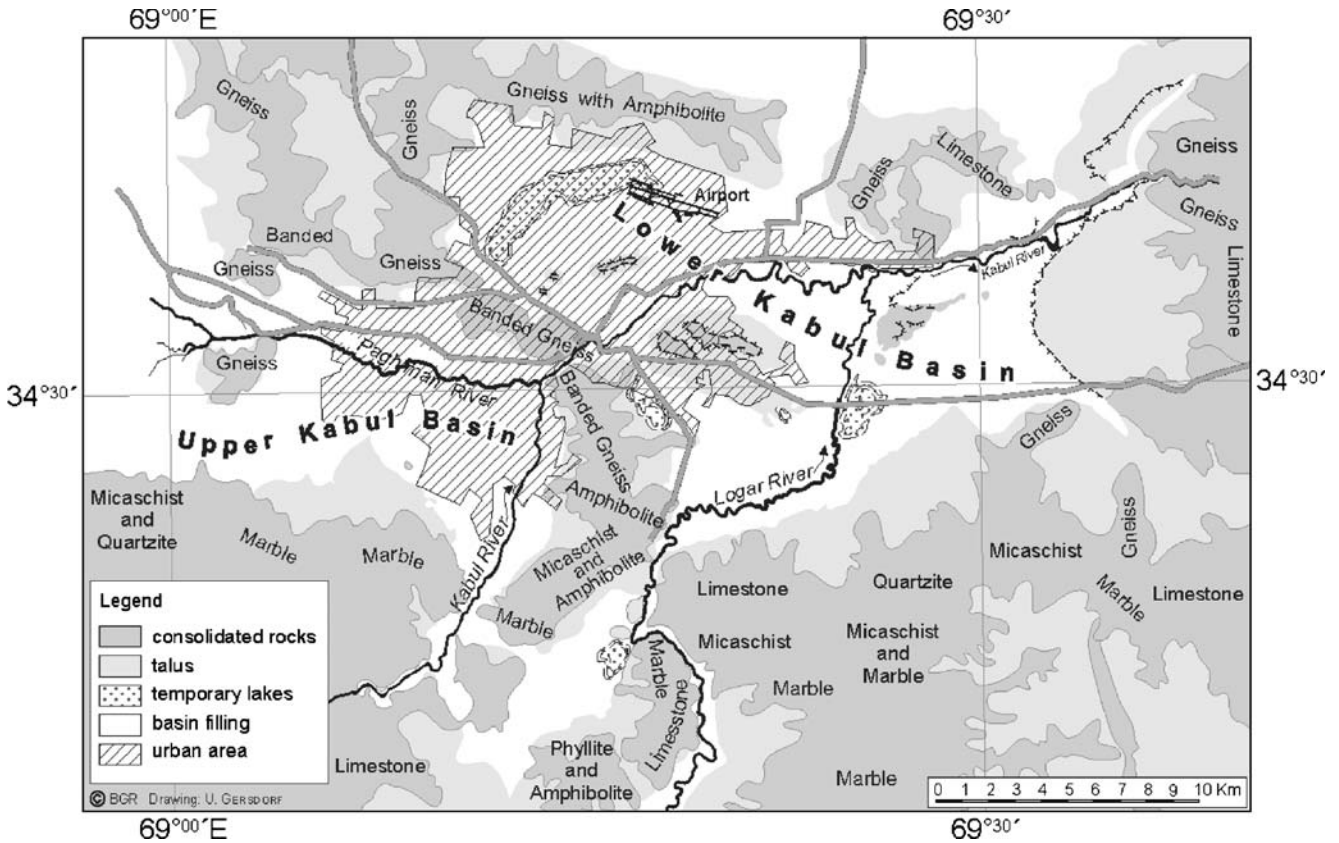
Fig. 2 Simplified geology of the Kabul region and study area. The unconsolidated aquifers are present in all areas without hard rocks (*grey shading*)

material can thus be classified as permeable to very permeable. The gravel bodies act as one hydraulic system without larger internal separating or confining layers. The pore spaces of the deeper parts of the aquifers are often partially cemented by secondary mineralisation processes (Fig. 3). Well yield therefore often decreases with depth. At present, due to the drought and the heavy abstraction, all aquifers are unconfined. During more humid times in the past, depth to groundwater could be low enough to cause (semi-)confined conditions with the low-permeability loess acting as the confining layer. The marly Kabul Formation with its low permeability forms the basal layer for all aquifers. The loess deposits form the protective top layer. In the vicinity of the river courses they are sometimes
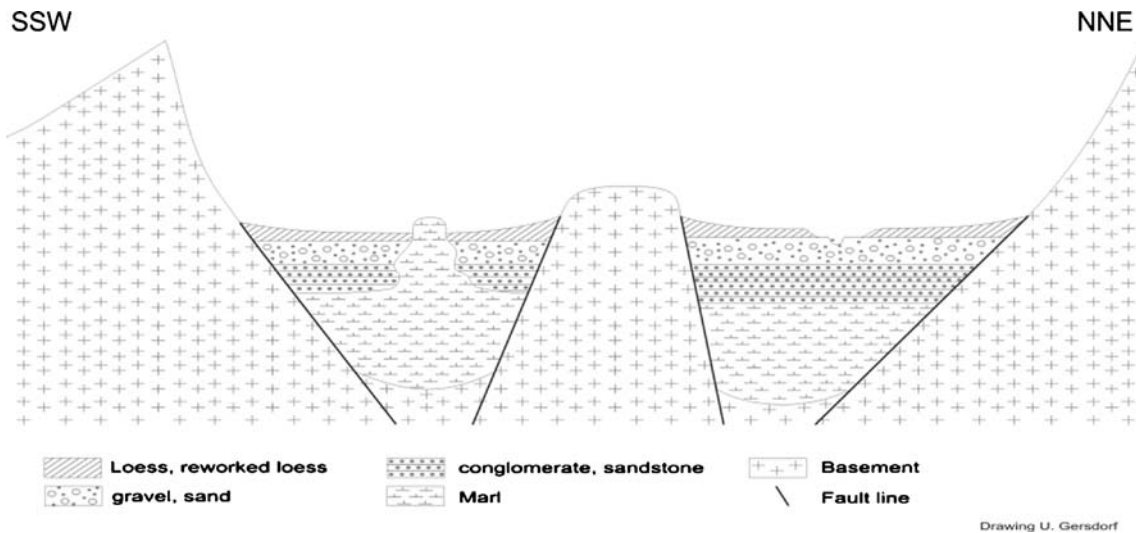

Fig. 3 Schematic geological profile of the Kabul Basin (approximate length: 25 km)

eroded. Intercalations of loess and gravel at the top of the main aquifers sometimes result in small-scaled perched aquifers. These usually only have low productivities and are exploited by shallow shaft wells. During periods of drought they easily fall dry.

The ground surface of the basin ranges from 1,830 m above sea level (m asl) in the west to 1,770 m asl at the eastern outlet. The Kabul Basin drains to the north-east through the very narrow gorge of Tangi Gharu (gauge 4 in Fig. 1). All groundwater and surface water must squeeze through this 'needle hole'. A generalised isopotential map is available from Broshears et al. (2005). Accordingly, the general groundwater flow direction is from the western or south-western basin margin, through the basin centre, to the north-eastern basin margin.

Logar aquifer

The Logar aquifer (Figs. 5 and 6) extends along both sides of Logar River over a length of 10 km and a width of around 3 km. It has an average thickness of 30 to 40 m and a maximum thickness of 70 m. The lower parts of this aquifer consist of coarse-grained deposits, mainly conglomerates and coarse-grained sandstones cemented by calcareous pore fillings. In the southern parts in particular, the deposits in the lower zones of the aquifer are interbedded with clay layers with thicknesses of 10–15 m and more.

Pump tests indicate that the hydraulic conductivities of the Logar aquifer are high but subject to some heterogeneity (1.4×10^{-4}–1.3×10^{-3} m/s). Analysis of the groundwater contours reveals that groundwater recharge to the Logar aquifer took place in the winters of the 1970s at elevations above 1,793 m (Fig. 6). Additional recharge is expected from infiltration from irrigation channels during the summer. Satellite images show that up to 50 km^2 are irrigated in the Logar river valley. Groundwater flow at the 1,790-m groundwater contour was estimated to be around 32,000 m^3/day in 1971. Groundwater infiltrates the river below the 1,792-m groundwater contour line (Fig. 6).

Kabul aquifer

A zone of coarse-grained deposits with a length of 9 km and a width of 2.5 km has been confirmed as running parallel to Kabul River. This zone comprises most of the Kabul aquifer. Analogous to the Logar aquifer, the Kabul aquifer consists of three horizons (Fig. 7). The main part of the aquifer consists of conglomerates and sandstones covered by a thin layer of sand and gravel. The cover rock consists of loess. The loess layers have a thickness of 1–5 m but thicknesses of up to 15 m were measured at the edges of the plain. The thickness of the sand and gravel layer in the higher parts of the plain is only 2–9 m, in the lower zones it is up to 20 m thick. The conglomerate and sandstone layer has a thickness of 30–65 m. The whole aquifer has a total thickness of 40–80 m.

The permeabilities in the conglomerate and sandstone bed range from 0.5×10^{-4} to 7.5×10^{-4} m/s. They can therefore be classified as permeable to very permeable. Because the sand and gravel deposits are thin, particularly in the southern part of the aquifer, the permeability is largely dependent on the conglomerates and sandstone.

Paghman aquifer

The gravel bed located along Paghman River in the Paghman-Darulaman Basin is around 10 km long, 4 km

Age		Name	Marginal deposits	Central deposits
Holocene	Würm	Reworked Loess Series	reworked loess, talus, gravel	reworked loess, clay alternating with gravel, conglomerates
Pleistocene	Cromer	Lataband Series	Lataband gravel / conglomerates	conglomerates, gravel (local)
		Kabul Series	loess, soil / sandstones, conglomerates, marls, clays / ?	marls, clays, siltstones, sandstones / ?
Neogene		Butkhak Series	red silts and sandstones clays, conglomerates	?
			Basement complex (bordering mountains)	

Fig. 4 Schematic stratigraphy of the Kabul Basin
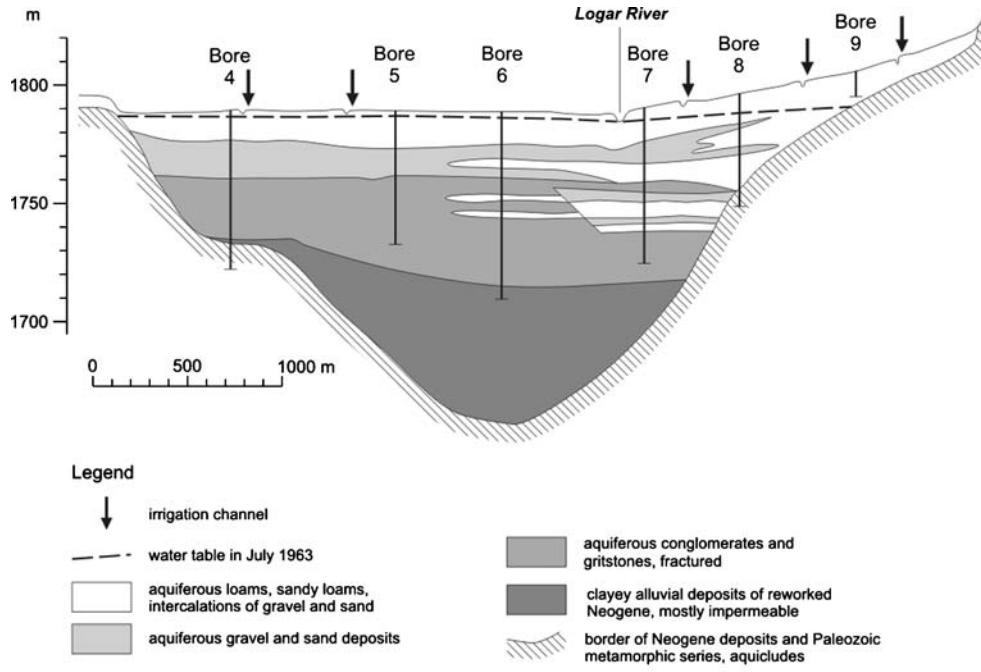
Fig. 5 Hydrogeological profile of the Logar aquifer (redrawn after Böckh 1971)
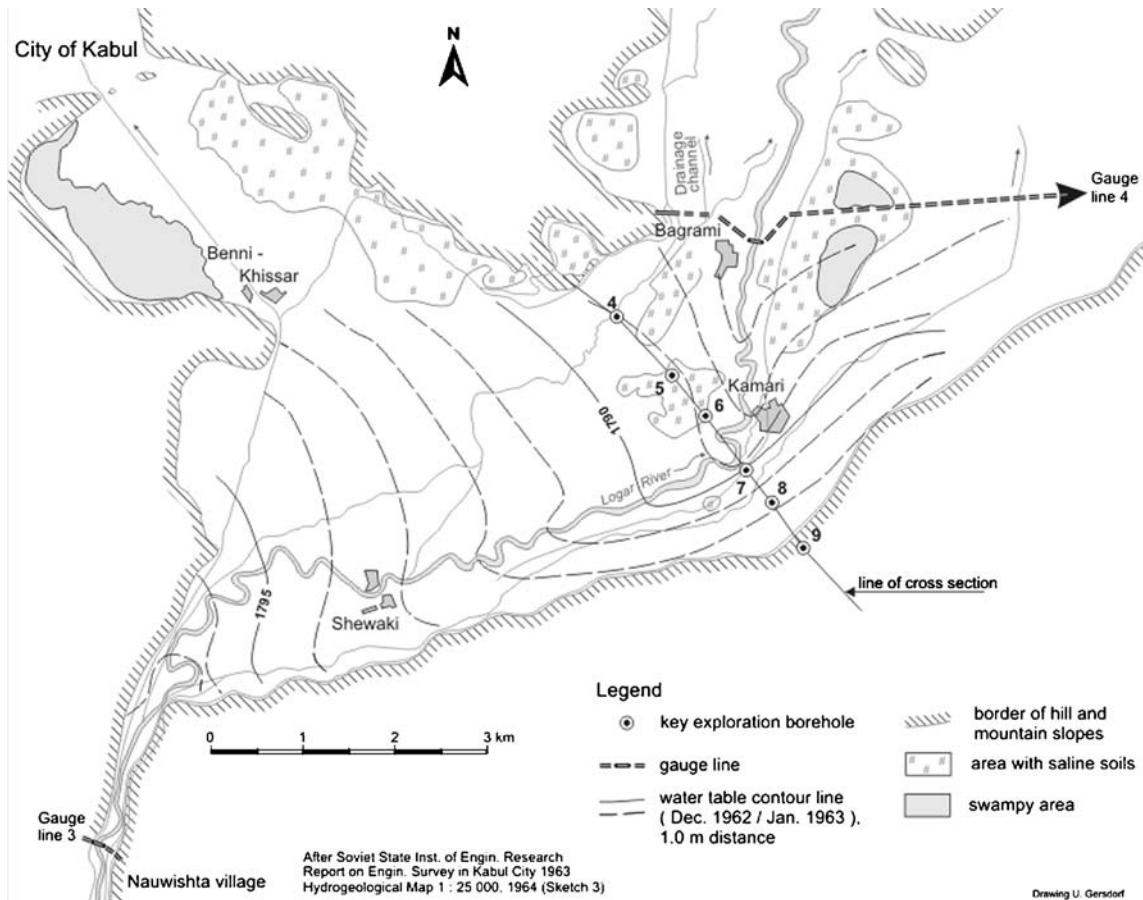

Fig. 6 Hydrogeological map of the Logar aquifer (after Böckh 1971). The depicted area is located between gauge 3 and south of gauge 4 in Fig. 1. The cross section is shown in Fig. 5
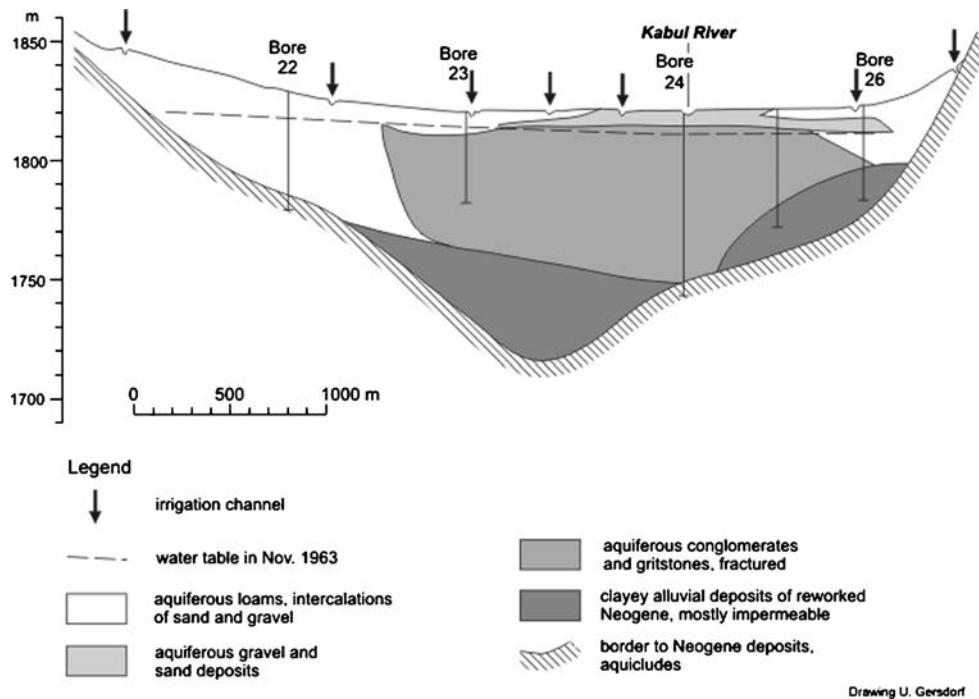
Fig. 7 Hydrogeological cross-section of the Kabul aquifer (after Böckh 1971)

wide, 45 m thick with local thicknesses of up to 70 m. This phreatic aquifer consists mainly of gravel and sand. Conglomerates and sandstones only occur in minor amounts at certain localities. It is therefore considered to be the best aquifer in the basin. The permeability of the aquifer ranges from 0.2×10^{-4} to 3.0×10^{-4} m/s and is therefore permeable. Permeability is more or less uniform throughout the aquifer.

Climate data

The climate in Kabul is arid to semi-arid with considerable day-time and night-time temperature fluctuations. The winters are characterised by low temperatures of down to -10°C and moderate precipitation (Fig. 8). The summers are dominated by high temperatures of up to 50°C in part combined with drought conditions. The temperature at the ground surface fluctuates in summer by more than 50°C during one day, whilst temperature fluctuations of up to 30°C are possible during the winter.

Precipitation
Continuous precipitation data for Kabul, recorded at the airport, are available only as monthly averages for the period 1957–1977 (Figs. 8a and 9a). Annual averages have been calculated from this data (Fig. 9a). The graph in Fig 9a clearly shows the major fluctuations from year to year: for instance, the average annual precipitation in 1959 was around 520 mm, whilst precipitation was only slightly over 155 mm in 1970. The average figure for the 21 years covered by this data is 330 mm, and therefore reflects a

very dry climate. Drought periods of several years are not uncommon, e.g. 1969–1971, 1973–1977 as well as the recent dry period (2000–2005).

The averaged "standard year" derived from the monthly average values for 1957 to 1977 (Fig. 8) highlights the changes in precipitation during the course of a typical year. The monthly precipitation in winter and spring varies between 20 and 80 mm. In summer, i.e. the period from June to October, the precipitation is considerably below 3 mm. March and April are the months with the highest precipitation rates.

Precipitation in winter occurs mainly in the form of snow. Snowfall records for Kabul are available for the period 1958–1971. The year with the most snow was the winter of 1963/1964 with almost a metre of snow. The months with the greatest snowfall are January and February with an average snowfall of 16 cm. The average number of days with snowfall is approximately 15 days from November to March. The month with the longest period of snowfall is December with an average of approximately 23 days.

Temperature
The air temperature values for Kabul which are also measured at the airport are also present in the form of monthly averages for 1957–1977 (Fig. 8b) and the annual averages calculated from these figures (Fig. 9b). These plots also show fluctuations. In 1964, the annual average temperature was only slightly over 10°C whilst the annual average temperature in 1970 was almost 13°C. A comparison of the precipitation and temperature plots during the observation period clearly shows that years
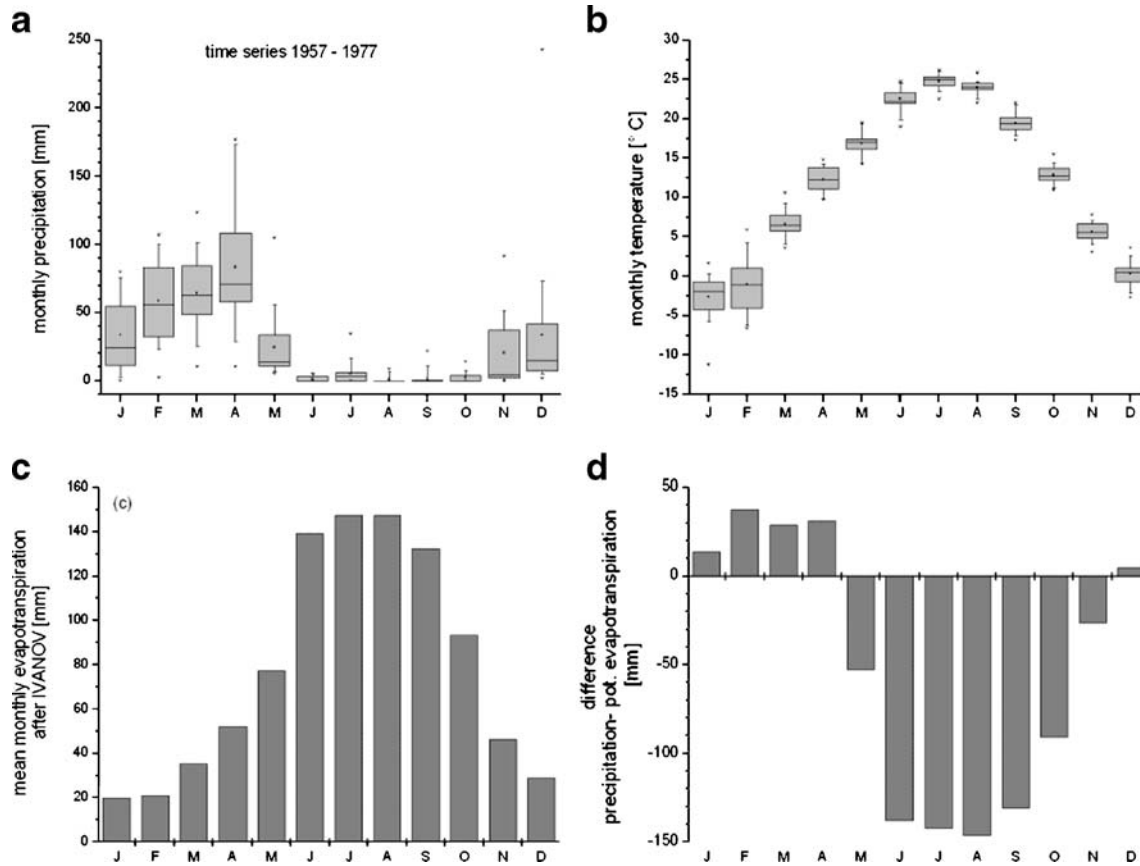
Fig. 8 Monthly averages of **a** precipitation, **b** air temperature, **c** potential evapotranspiration (ET$_{pot}$ calculated after Ivanov 1954) and **d** difference between precipitation and evapotranspiration, station Kabul Airport 1957–1977

with high average temperatures also have low precipitation. If the annual average temperature is relatively low, they usually correspond with above average precipitation (Fig. 9a,b). These facts highlight the irregular climatic conditions revealed for the 21-year observation period by the precipitation and temperature changes.

A standard temperature distribution for a typical year can also be derived only from the monthly averages from 1957–1977 (Fig. 8b). The annual average temperature is 10.8°C. The average temperatures during the course of the year vary between −3°C in the winter months (January, February) and +25°C in the summer months (June to August). A comparison of the precipitation and temperature plots clearly shows that years with high average temperatures also have low precipitation. Years with low average temperatures usually correspond with above average precipitation (Fig. 9a,b).

Evapotranspiration

Evapotranspiration is determined as part of this study using two different formulae: the first after Ivanov (1954) with the help of average monthly figures, and the second after Turc (1961), taking into consideration the annual averages for temperature, precipitation and air humidity.

A modified Ivanov (1954) approach was used to calculate potential evapotranspiration Eq. (1). The advan-

tage of this method is that it can also take minus temperatures into consideration.

$$ET_{p\ Ivanov} = 0.0011 \times (T + 25)^2 \times (100 - U) \qquad (1)$$

where T = mean monthly temperature (°C), U = relative humidity (%).

This equation can be used to calculate the monthly evapotranspiration from the average monthly figures for air temperature and air humidity. The input data for the calculation was the temperature data recorded at Kabul airport from 1957 to 1977, and recorded average monthly air humidity (not shown) for 1959–1964 (Fig. 8c).

The comparison of precipitation with the potential evapotranspiration calculated according to Ivanov (Fig. 8c) clearly shows that evaporation from April to November is much higher than the precipitation—usually with a difference of over 120 mm. This situation is also clearly seen in Fig. 8d, which shows the difference between fallen precipitation and calculated evapotranspiration. According to this, groundwater recharge, if at all, only takes place from December to April. However, because precipitation during this period mainly falls in the form of snow and is therefore lost during snow melting, partially also by surface discharge, the volume of precipitation actually available for groundwater recharge is probably much lower, particularly because part of the
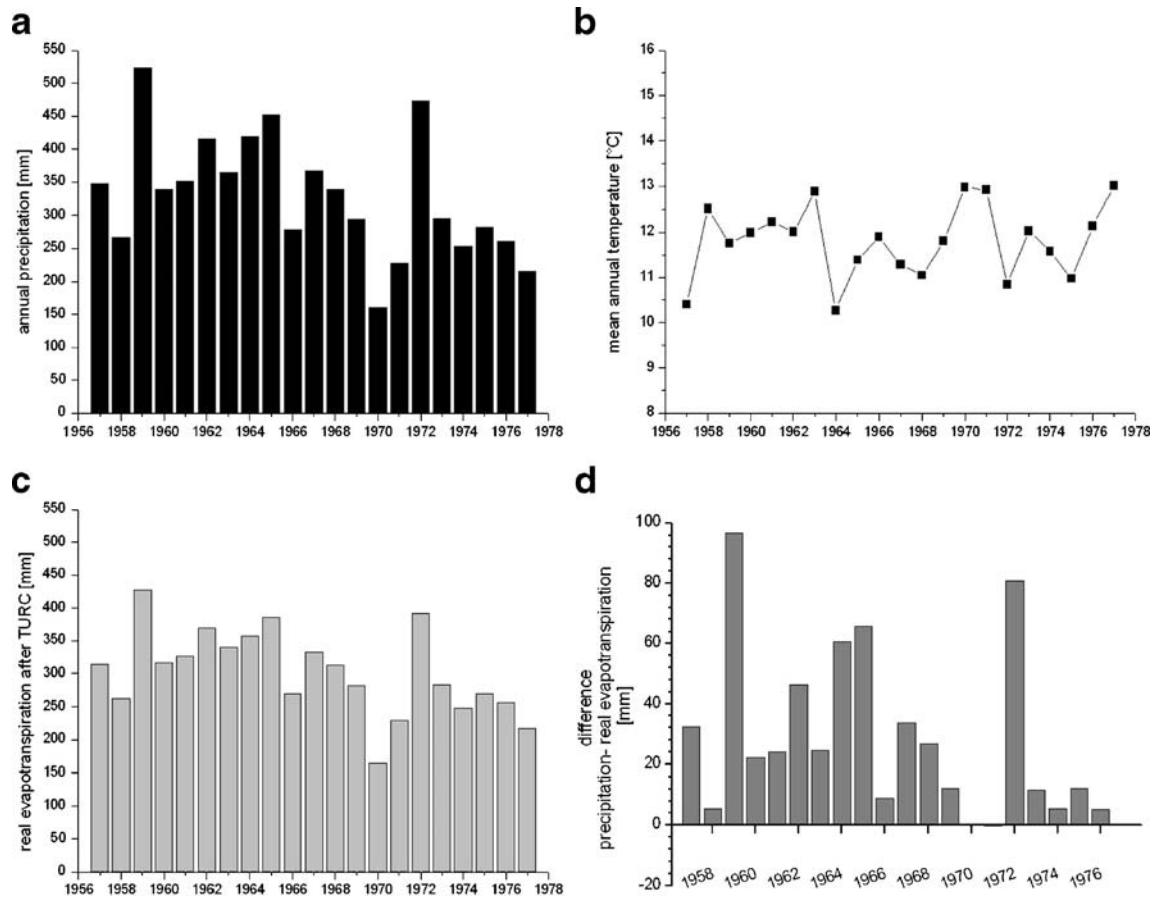
Fig. 9 Annual averages of **a** precipitation, **b** air temperature, **c** evapotranspiration (ET_real calculated after Turc 1961) and **d** difference between precipitation and real evapotranspiration, station Kabul Airport 1957–1977

assumed excess serves to maintain or re-establish the moisture of the soil.

Approximate annual averages for real evapotranspiration can be calculated using the equation is according to Turc (1961):

$$\mathrm{ET_{real}} = \frac{P}{\left[0,9 + \left(\frac{P}{J_t}\right)^2\right]^{0,5}} \qquad (2)$$

where P = mean annual precipitation (mm), $J_t = 300 + 25\,T + 0.05\,T^3$, T = mean annual temperature (° C)

The input values are the precipitation and temperature figures recorded at Kabul airport from 1957–1977, or the averages calculated from these data (Fig. 9a,b). Figure 9c clearly shows that the evapotranspiration largely coincides with the degree of precipitation. If there is more precipitation, more water is available for evaporation. Because the real evapotranspiration in almost all years is below the figure of fallen precipitation (Fig. 9d), it is possible, at least in theory, that groundwater recharge took place in all years which fulfil this criterion. However, because the proportion of precipitation which fell as snow and other losses are not taken into consideration in this balance, it is only possible to make estimates here on the

possibilities of groundwater recharge, particularly because the influence of buildings and vegetation is unknown. The average possible groundwater recharge from Fig. 9d is 32 mm/a ignoring all potential losses. This value can therefore be taken as the maximum possible groundwater recharge rate. Therefore it is unlikely that significant groundwater regeneration from precipitation comprised a major contribution to recharge from 1957 to 1977, and that it is also probably not overly important today.

Groundwater recharge

Groundwater recharge in the Kabul Basin comprises various components which are listed below according to their assumed importance.

– Infiltration from surface waters
– Foothill infiltration, i.e. infiltration of surface runoff at the basin margins (transition consolidated to unconsolidated rock)
– Direct recharge from precipitation
– Infiltration from irrigation ditches
– Seepage of domestic sewage and industrial effluent

The main contribution to the groundwater recharge in the Kabul Basin comes from infiltration along the rivers

(at least during the high water period when the snow thaws). An Afghan proverb states that "Kabul may be without gold but it cannot be without snow". Surface infiltration at the basin rim, at the border between consolidated and unconsolidated rocks may play a part although it is difficult to quantify. The US Geological Survey (USGS) geological map in Broshears et al. (2005) correspondingly shows sand and gravel formations along the margins of the basin. These contributions can be significant because of the steep slopes and the amount of snow accumulating on the surrounding mountains. The percolation of domestic sewage and industrial effluent does not have any particular effect on the groundwater balance because the infiltrating water was originally extracted from the aquifer. However, this aspect is extremely important when assessing the contamination of the aquifers in the Kabul Basin (see part II of this study, Houben et al. 2008). From the climatic data one can infer that the maximum average groundwater recharge rate from rain for the studied period would be about 32 mm/a (Fig. 9d), around 10% of precipitation. However, as discussed above, one can assume that the actual percentage of precipitation which could recharge directly into the groundwater would be even smaller than the above figure suggests.

Depth to groundwater

In 1965, the water table within the city of Kabul was very close to the surface at depths of 2–5 m. Groundwater level fluctuations of up to 5 m over the course of 1 year have been observed although fluctuations of 1–2 m were more common. Changes in water levels were connected directly to the seasonal climatic and run-off variations. Maximum groundwater levels coincide with the melting of the snow in April and May. The highest fluctuations occur in wells close to the rivers which confirms the hydraulic connection between river and groundwater.

Recent recordings of the fluctuations in piezometric levels were obtained from a well monitored by the Danish NGO DACAAR (Danish Committee for Aid to Afghan Refugees) in the town district of Shar-I-Nau (Fig. 10). Today the depth to the water table is 8–10 m. The annual amplitude is about 2 m. According to BGR file data the depth to water table in the same area in 1965 was around 2–3 m. The water table has thus dropped approximately 6–7 m as a result of intense extraction, population increase and the climatic variations during recent years. These changes are also clearly noted in the many dry shaft wells which are now common within the city.

Hydrography

Logar River and Paghman River are each equipped with one river gauge, whilst the discharge of Kabul River can be measured from two gauges, one upstream of the confluence of Paghman and Kabul rivers, and one downstream of the confluence of Logar and Kabul rivers
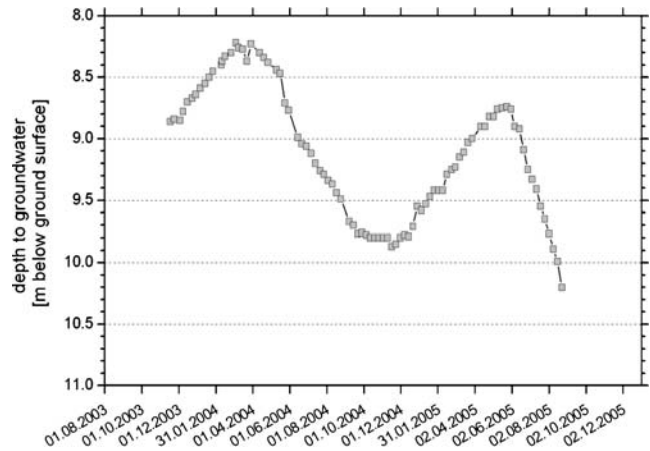

Fig. 10 Depth to groundwater in a well in Kabul city (unpublished data, courtesy of Didier Vanden Berghe, DACAAR, 2006). Date format dd/mm/yyyy

(Fig. 1). All gauges fell out of use during the wars so that newer data are missing.

Logar River flows into the Kabul Basin from a southerly direction and flows into Kabul River in the central part of the basin. The Logar drains 78% of the total catchment area of the Kabul River to the point where it flows into Kabul River (Fig. 1). The recorded drainage values (Fig. 11b) show that the annual drainage from October 1961 to September 1964 fluctuated between 8.9 and 10.8 m³/s.

Kabul River flows into the Paghman-Darulaman Basin from the south-west and flows out of the Kabul Basin in an easterly direction. Paghman River flows into Kabul River shortly before Kabul River enters the Kabul Basin. Kabul River then flows through the central part of the Kabul Basin and leaves the basin towards the north-east, 12 km after the confluence with the Logar. Kabul River ultimately flows into the Indus, Pakistan's most important river. Kabul River itself drains around 13% of the catchment area of the catchment (Fig. 1). Average annual discharge fluctuated from October 1961 to September 1964 between 2.2 and 5.6 m³/s (Fig. 11).

Paghman River, which drains around 3–5% of the catchment area flows into Kabul River from a westerly direction in the Paghman-Darulaman Basin. The discharge is strongly affected by the extraction of irrigation water. Average discharges of 0.9 m³/s were recorded in the 1963/1964 hydrological year at the Pule Sokhta gauge (Fig. 11a). The Paghman therefore has the smallest discharge of all the rivers in the Kabul area.

The Tangi Gharu gauge has the longest series of recordings covering a period of 5 ears (Fig. 11d). The highest flows occur between March and May, which are also the months with the highest rainfall rates (Fig. 8). It is also the period for the beginning of the snow melt as the monthly mean temperature rises rapidly from February. From June to September, which is the period with the lowest precipitation and highest irrigation water demand, there is hardly any water flow in Kabul River. If one compares the data for April and May, the months with the
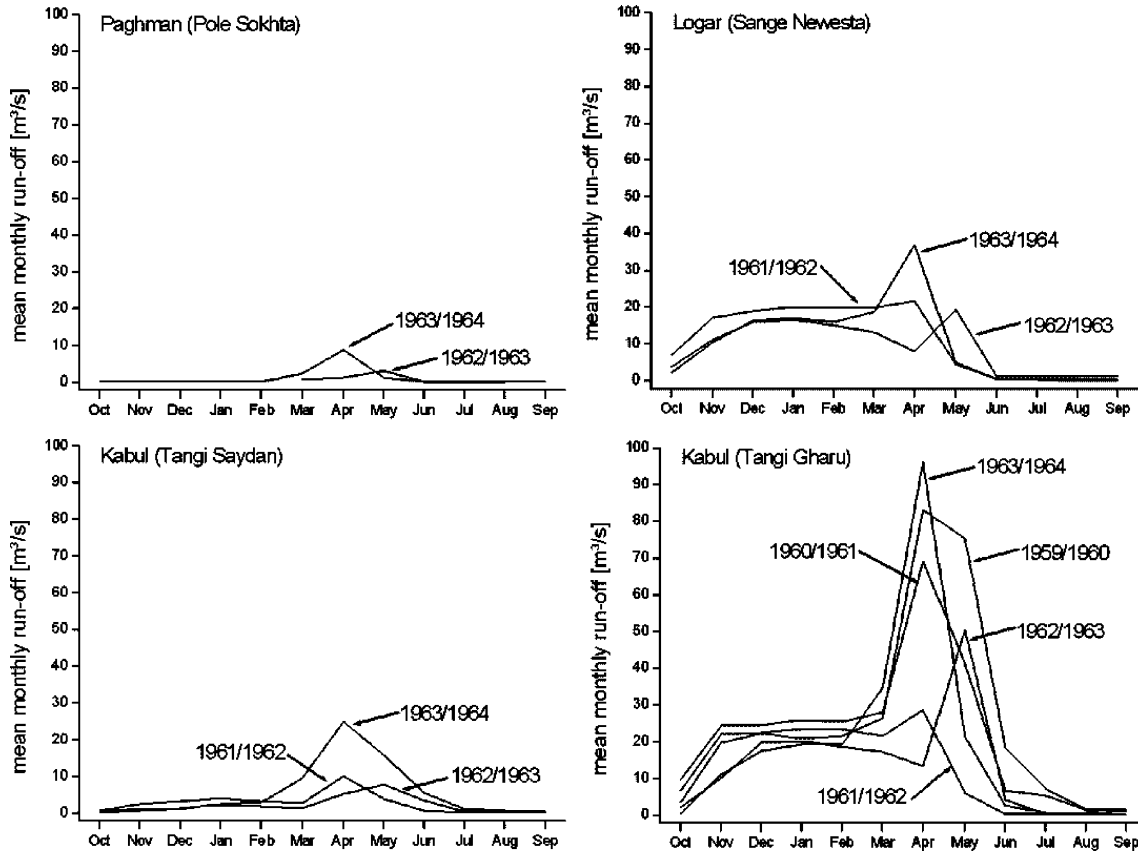
Fig. 11 Run-off of the rivers **a** Paghman, **b** Logar and **c–d** Kabul. The lower figures show the run-off of Kabul River before (Tangi Saydan, **c**) and after (Tangi Gharu, **d**) joining with Paghman River and Logar River

highest discharge and precipitation rates for 1963 and 1964 (the years for which data are available from all of the gauges), then it is clear that Kabul River has a higher discharge than the sum of its tributaries. This could indicate some direct surface runoff during periods of higher precipitation. However, the impact of the groundwater inflow on the increase in discharges should not be ignored. According to the USGS isopotential map of the Kabul Basin (Broshears et al. 2005), groundwater infiltrates into Kabul River around Tangi Gharu. Since the aquifer practically pinches out at the gorge, the river gauge there is essential for all further water budget calculations.

During the recent drought period, the rivers hardly carried any water at all. This of course precluded any groundwater recharge. Since abstraction of groundwater continued unabated, groundwater levels have, of course, decreased as shown above. Several wet years would probably be needed to raise the levels to some degree again.

Water consumption

Water demand is a function of the population number and the water consumption per capita. Studies report that there were 320,000 inhabitants in the city in 1962, 590,000 in 1972 and 1.8 million in 2001. In 2005 the population was estimated to be around 3 million, maybe more. No precise

information is available on industrial water demand. Nevertheless, there is hardly any industry and most goods are imported. The withdrawals used for irrigation are difficult to estimate. The irrigation season starts in April and ends in October with highest intensity between June and September. Irrigation does not affect the whole study area, as it occurs only in some parts of the catchment, mainly in the Logar valley.
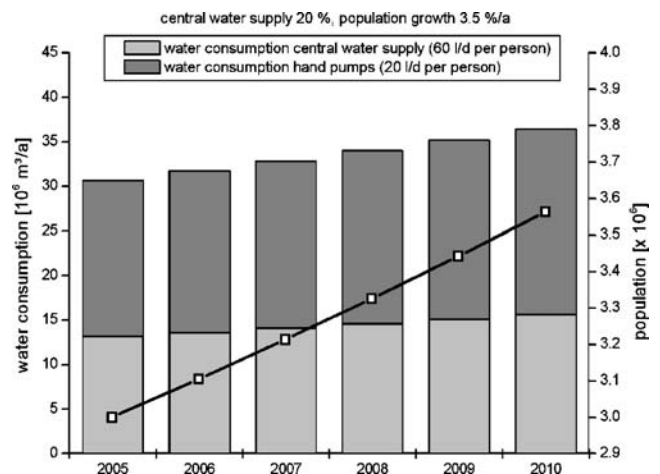

Fig. 12 Prognosis of water consumption (*bars*) and population development (*line*) for Kabul

Table 1 Estimation of water demand as a function of water consumption and population

No. of inhabitants	Consumption (litre/day/person)			
	20	40	60	100
	Water demand (x 10^6 m^3/a)			
320,000	2.34	4.67	7.01	11.68
590,000	4.31	8.61	12.92	21.54
1,800,000	13.14	26.28	39.42	65.70
3,000,000	21.90	43.80	65.70	109.50
3,500,000	25.55	51.10	76.65	127.75
4,500,000	32.85	65.70	98.55	164.25

Due to the lack of a metering system, no reliable data on water consumption are available. Assuming a population of 3 million people in 2005, it is estimated that the consumption today is at least 30 million m^3/a (Fig. 12). This is, in part, based on an unpublished survey by the German Kreditanstalt für Wiederaufbau (KfW) that assumes that 80% of the population depend on hand pumps and 20 L of water are carried home each day for each member of the family. The remaining 20% have access to piped tap water. Water consumption in these privileged households is estimated to amount to 60 L/day and per person. Table 1 shows some possible variations of water demand as a function of population and per capita consumption.

Due to the absence of a wastewater disposal network, some proportion of the wastewater reinfiltrates into groundwater. The authors estimate that at least one third re-enters the aquifers, while the remainder is lost, mostly due to evaporation during cleaning, cooking and laundry activities.

Water budget calculations and flow modelling

Numerical groundwater flow modelling was undertaken to broaden the understanding of the hydrogeological behaviour of the groundwater system. The model only simulates the groundwater flow in the saturated zone. Processes of surface run-off and in the unsaturated zone were not taken into account. The sparcity of data and their sometimes doubtful quality underline that this model only is of conceptual value and may at this stage not be used for resources management. Even though, the estimates give a rough idea of the general hydrology and hydrogeology in Kabul.

The commercial finite element software SPRING was employed (delta h, Dortmund, Germany). A USGS digital elevation model (DEM) with a 90 m × 90 m resolution raster was used to generate the ground surface for the numerical model. Estimates of the aquifer thickness were inferred from geological maps and profiles. Minimum aquifer thicknesses were assumed to be 3 m at the borders of the model and could reach 30 m and more into the centre of the basin. The borders of the model were determined from the elevation model and geological maps. The 1,830-m contour line was chosen for the northern boundary, which corresponds approximately to the base of the mountains, and the 2,000-m contour line for the southern border where the slopes of the mountains are lower and large debris fans are present. The Tangi Gharu gorge was interpreted as the sole outlet of the system (Fig. 1). The total area of the model is about
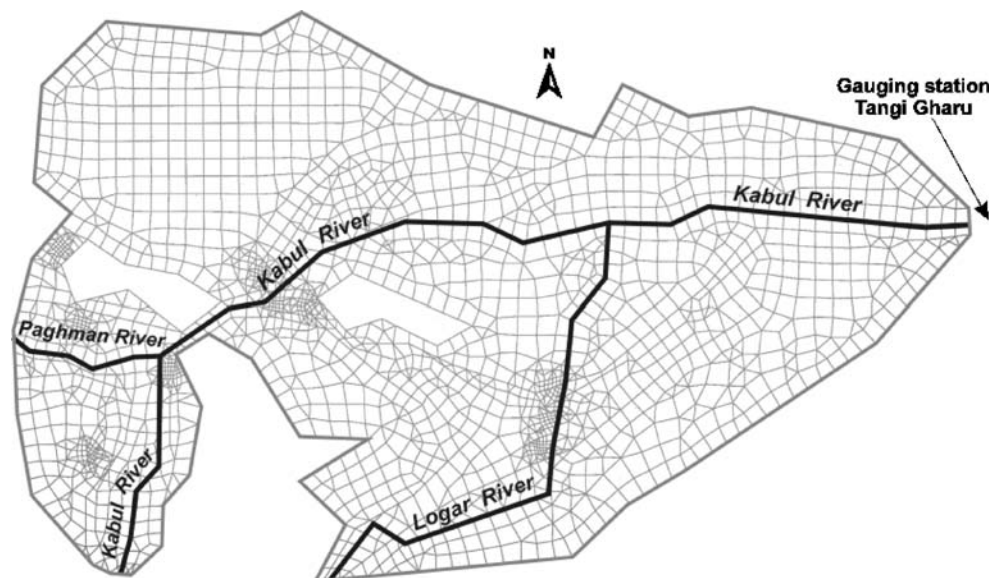

Fig. 13 Grid of the numerical flow model (grid width 27 km)

Table 2 Estimation of total aquifer storage considering different thicknesses and porosities

Average aquifer thickness (m)	Effective porosity		
	0.075	0.10	0.13
	Total storage (x 10^6 m^3)		
30	833	1,110	1,443
40	1,110	1,480	1,924
50	1,388	1,850	2,405

370 km^2 (approximately 33 km long and 18 km wide). The model grid contained 10,005 nodes and 11,159 elements (Fig. 13). Considering the lack of precise data concerning the current abstraction rate and the thousands of small wells, the current withdrawal was simulated as negative recharge in the heavily populated urban areas (63.3 km^2) which were identified from a topographic map dated 2002. Run-off water from the surrounding mountains was assumed to infiltrate along the valley flanks. The basin margins were thus modelled as preferential zones for foothill infiltration. Both foothill infiltration and infiltration from the rivers was possible in the model. Well water levels were taken from Broshears et al. (2005). Recent recordings of the fluctuations in piezometric levels were obtained from a well monitored by DACAAR (Fig. 10).

Considering groundwater recharge rates from precipitation of 20 and 32 mm/m^2/a for the whole surface of the model area (370 km^2), the total annual recharge volume is 7.4–11.8·10^6 m^3/a. One can immediately see that this figure is far lower than even conservative estimates of water demand (Table 1). Foothill infiltration and river infiltration have to fill the gap. In dry years when both recharge from precipitation and river infiltration are low, the water budget becomes negative and practically all abstraction is taken from storage. The total storage in the aquifer corresponds to the total amount of water stored in the aquifer, and can be estimated from average values of effective porosity and the spatial dimensions of the aquifer (Table 2). The calculated amounts of water are high enough to provide the inhabitants with a buffer of several years, but at the price of sinking water levels and increased concentrations of pollutants. The turnover rate of the aquifer (as percentage) was calculated as the ratio of average recharge over total storage (Table 3).

Despite the lack of reliable data, model variations were performed until realistic results were obtained. These were obtained using hydraulic conductivities in the range of 1×10^{-4} to 1×10^{-3} m/s. The models yielded values for total foothill infiltration of around 5×10^6 m^3/a and total

infiltration from the rivers of about 15×10^6 m^3/a to 25×10^6 m^3. Total recharge in wet periods from all mechanisms could thus be anywhere between 15×10^6 and 40×10^6 m^3/a. The current demand for drinking water is in the range of 30×10^6 to 40×10^6 m^3/a (Table 1). Recharge in wet years and current demand are therefore in fragile balance. With a further increasing population and potentially increasing water consumption due to development, the demand could eventually exceed recharge even in wet periods.

The model convincingly showed that groundwater generally flows from the west to the eastern part of the basin. The rivers recharge groundwater in the western parts of the basin and drain groundwater in the eastern part. This coincides with the general geomorphology of the basin.

Summary and outlook

The city of Kabul is underlain in most parts by shallow unconsolidated to semi-consolidated aquifers of sufficient thickness and hydraulic conductivity to constitute a viable resource. Due to the irregularity of surface-water availability, groundwater is now the most common source of water supply. The aquifers are in most parts protected by less permeable loess loams layers. Unbuffered infiltration of pollutants can occur at the river courses where the loess has been eroded and locally where the loam was removed to make building material or to excavate latrines.

Groundwater recharge is heavily dependent on infiltration from surface-water bodies during the few months of snow melt; foothill infiltration and direct recharge from precipitation could also represent a part of the recharge. In the not uncommon event of extended droughts, groundwater abstraction is taken from the stored volume, quickly leading to falling water levels. The strongly increasing population is putting a lot of stress on the water budget due to the increasing water demand which in future may exceed recharge rates even in wetter periods. Artificial recharge of peak flow river water might be a useful option to increase available groundwater. The lack of proper wastewater disposal leads to massive influx of polluted water into the aquifer (see part II of this study, Houben et al. 2008).

For successful future water resources management, the reconstruction of the weather stations and the river gauges and the implementation of groundwater monitoring are essential. The full reports of BGR activities in Kabul may be downloaded free of charge from BGR (2005).

Table 3 Turnover rate of total storage considering different recharge rates

Annual groundwater recharge volume (x 10^6 m^3)	Total aquifer storage (x 10^6 m^3)				
	833	1,110	1,443	1,850	2,405
	Annual turnover rate (%)				
25	3.0	2.3	1.7	1.4	1.0
45	5.4	4.1	3.1	2.4	1.9

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