Hydrogeology of the Kabul Basin (Afghanistan), part II: groundwater geochemistry

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Abstract Shallow groundwater is the main source for drinking water in Kabul, Afghanistan. It comes from a multitude of shallow hand-pumped wells spread over the whole city area. The groundwater is characterised by slightly oxic redox conditions. Interactions with aquifer carbonates lead to near-neutral pH and high degrees of hardness. The mostly negative water budget of the Kabul Basin is the result of strong evaporation which leads to an increase in salt and also of some undesirable constituents, e.g. borate. Several years of drought have aggravated this problem. The shallow groundwater in the city has received tremendous amounts of pollution due to a lack of proper waste disposal and sewage treatment. Common indicators are elevated concentrations of nutrients such as nitrate and faecal bacteria. The high infant mortality can at least partially be attributed to the insufficient water hygiene. Acid generated during the mineralisation of the wastewater is hidden due to the strong pH buffering capacity of the groundwater system. Redox and pH conditions preclude significant mobilisation of trace metals and metalloids.

Keywords Afghanistan · Urban groundwater · Arid regions · Infant mortality · Hydrochemistry

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Introduction

The inhabitants of Kabul, Afghanistan (Fig. 1) are largely dependent on shallow groundwater for their drinking water supply. Because of an extended drought period (2001–2005) and the destruction of the infrastructure as a result of wars and civil wars, groundwater is now a scarce resource. Barely 20% of the inhabitants are connected up to the central water supply system. Consequently, the city has thousands of shallow hand-pumped wells which supply the drinking water of the majority of the population. Due to a massive influx of returning refugees after the demise of the Taliban regime, Kabul's population has increased sharply.

Sewage is largely disposed of in countless domestic drainage pits and shallow open sewage channels along the streets of Kabul. Therefore it is likely that the shallow aquifers are contaminated by influxes of contaminants. This probably contributes to the high infant mortality rate which is largely attributable to water-borne diseases (UNICEF 2008). As part of a project financed by the Foreign Office of the Federal Republic of Germany, the Federal Institute for Geosciences and Natural Resources (BGR), together with Afghan colleagues, conducted a groundwater sampling survey in the urban area of Kabul in 2004 (BGR 2005). The aim of this analysis was a comprehensive characterisation of the water quality. Special attention was given to drinking water hygiene and the anthropogenic contamination of groundwater. The information acquired in this way is an important source of information for future sustainable management of groundwater resources in the Kabul Basin.

Materials and methods

From April to August 2004, 290 shallow and deep wells in the city of Kabul were sampled and the specific well data and the associated onsite hydrochemical parameters recorded. Specific well data included location description, global positioning system (GPS) co-ordinates, well type and construction type, pump type and service life (if any) and static groundwater level. About 85–90% of the city area was included in this survey. The minimum distance between the surveyed wells was 500 m. In addition, in late July/August 2005, eight surface water samples were taken and analysed.



Fig. 1 Schematic map of the Kabul Basin

The largely agricultural surroundings of Kabul were not included in this study because of security reasons. This region was also sampled by experts of the US Geological Survey (USGS) in 2004 (Broshears et al. 2005).

Multi-parameter measuring equipment from WTW, type Multi 340 was used for the onsite analysis. These were equipped with appropriate measuring probes (all by WTW):

- pH, temperature: Sentix 41
- Redox potential: Sentix ORP
- Specific electrical conductivity (EC): TetraCon
- Dissolved oxygen: CellOx 325

The concentration of the dissolved inorganic carbon species bicarbonate, carbon dioxide and carbonate were determined, where relevant, by onsite titration. The alkalinity of the water samples was determined from a 100-ml aliquot by titration with 0.1 N HCl to an end point of pH=4.3. The end point is determined using a pH measuring apparatus (WTW-Multi 340i) with a glass electrode (WTW SenTix 41). The dissolved CO₂ concentration is determined analogously by titration with 0.1 N NaOH to an endpoint of pH=8.2.

The analysis of major and trace elements could not be carried out locally because of the absence of a suitable water laboratory in Afghanistan. The water samples (186 groundwater, 8 surface water) were therefore flown to Germany within days after sampling and analysed at BGR's hydrochemical laboratory in Hannover.

The anions F⁻, Cl⁻, Br⁻, NO₃⁻, SO₄²⁻ were analysed with ion chromatography (Dionex DX 500) using conductivity detection with a membrane suppresser technique (eluent: KOH; regenerant solution: H₂SO₄). The concentrations of the main elements Na, K, Ca, Mg, B, Al, Si, Mn and Fe and the trace elements Cd, Co, Cr, Cu, Ni, Pb, Sc, Ti and Zn were analysed using ICP-OES (Inductive Coupled Plasma Atom Emission Spectrometry, Spectro Ciros CCD). Samples were filtered in the field through a 0.45-µm cellulose acetate filter, previously conditioned with sample water. Samples were stabilised with 1-ml nitric acid (HNO3 suprapure) per 100 ml sample. Nitrite, ammonium and phosphate were analysed by photometer (Unicam UV 300). A map of the sampling points and the complete results from field and laboratory analysis for all samples are provided (see Electronic supplementary material).

Results

The analyses revealed that a large number of samples (40%) exceeded the limit of 1,500 μ S/cm for EC recommended by the World Health Organisation (WHO)—in other words, have salt concentrations which are too high for human consumption, at least in the long term (Fig. 2; see also Electronic supplementary material). Twelve percent of the samples would fail the European drinking water limit of 2,500 μ S/cm but because of the acute water shortage in Afghanistan, EC of up to 3,000 μ S/cm are tolerated for human consumption.



specific electrical conductivity (EC)

Fig. 2 Box-whisker diagram of specific electrical conductivity (EC) of groundwater in the Kabul Basin in 2004. Symbol legend: *square* refers to the mean, x is equivalent to 1 and 99% values, *dash* refers to minimum and maximum values

Reasons for the elevated EC could include:

- Percolation of sewage with high salt concentrations from drainage pits, road ditches etc. into the shallow groundwater
- Incineration of domestic refuse in road ditches
- Relative enrichment of salts during groundwater recharge (or use) as a result of strong evaporation
- Pollution (anthropogenic) via infiltration from Kabul River and Logar River

As a generalisation, the pH of the groundwater in the Kabul Basin lies in the very weak basic zone in more than 95% of cases, i.e. very close to neutral (Fig. 3). This



Fig. 3 Box-whisker diagram of groundwater pH in the Kabul Basin in 2004. Symbol legend: *square* refers to the mean, x is equivalent to 1 and 99% values, *dash* refers to minimum and maximum values

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indicates a well-buffered system. This is a very positive quality with respect to the mobilisation of heavy metals from the soil, and the corrosivity of the water. None of the samples exceeded the recommended limits.

Measured concentrations of calcium, magnesium and bicarbonate in the Kabul Basin reveal that the interaction of the groundwater with carbonate minerals must play a key role in its quality. The circum-neutral pH values also support this finding. Carbonate rocks are known from the area surrounding the basin (Malm limestones) and from the base of the basin (Pliocene limestones and marls of the Kabul series, see part I of this study, Houben et al. 2008). Waters in contact with limestone typically have molar Ca/ Mg ratios of approx. 2.0: 1 to 1.5:1 (Mandel and Shiftan 1981). Water in contact with dolomite $(CaMg(CO_3)_2)$ ideally has a ratio of approx. 1: 1. However, the dolomite ratios in reality are usually around 1.4: 1 to 1.1: 1 (Mandel and Shiftan 1981). Remarkably, the magnesium concentrations in the Kabul Basin samples are relatively high compared to the calcium concentrations (Figs. 4 and 5). Approximately 75% of all samples have lower values than those described above for a dolomite system, i.e. there is a magnesium excess, and the median figure for Ca/Mg lies at approx. 0.7: 1. The US Geological Survey investigations revealed a similar picture (Broshears et al. 2005). This indicates that there must be another source of magnesium—or a sink for calcium. A source of magnesium could be the metamorphic Precambrian rocks surrounding the northern and western basin margins, as well as the Palaeozoic phyllites in the south and east. Magnesium-rich metamorphic minerals include for example serpentine (Mg₆[(OH)₈/Si₄O₁₀]), talc (Mg₃[(OH)₂/ Si_4O_{10}), cordierite, garnet, chlorite and montmorillonite. The presence of such minerals can give rise to high magnesium concentrations in groundwater (e.g. Hem 1986). Investigations of surface water quality point in this direction. Analyses of Logar River in 2005 showed calcium 40 mg/l and magnesium 118 mg/l. A relative enrichment of calcium as a result of ion exchange is thought to be unlikely given the postulated dimensions and the similar sorption affinity of magnesium. Waters which have flown through dolomite and are saturated in this mineral can cause the precipitation of calcite for kinetic reasons. This removes calcium and gives rise to the relative enrichment of magnesium. Such processes have been suggested by e.g. Hem (1986), Stumm and Morgan (1996) and Schwartz and Ploethner (2000).

High calcium and magnesium concentrations make the groundwater "hard" or "very hard". This significant hardness gives the water a very high buffer capacity against acid input, which is useful, for instance, to buffer the formation of acid from the nitrification of ammonium. From a technical point of view, hardness is very undesirable due to the potential incrustation build-up in pipelines and household appliances. This needs to be taken into consideration particularly when considering the construction of a central water supply system. The significant hardness is of course associated with high carbonate hardness and bicarbonate concentrations. This



Fig. 4 Box-whisker diagram of calcium and magnesium concentrations in the groundwater of the Kabul Basin in 2004. Symbol legend: *square* refers to the mean, *x* is equivalent to 1 and 99% values, *dash* refers to minimum and maximum values

may be sourced from the dissolution of carbonate minerals or from the mineralisation of biomass (simplified "CH₂O"), e.g. from sewage, as given in Eq. (1).

$$"CH_2O" + O_2 \Leftrightarrow HCO_3^- + H^+ \tag{1}$$

The saturation state of the water expressed by the saturation index SI, with respect to calcite $(CaCO_3)$ and dolomite, $CaMg(CO_3)_2$, is a very important parameter for technical applications. It is essential to determine whether the water contains more or less dissolved carbonate than required for equilibrium. The water is either carbonate-oversaturated (SI>0) and therefore can give rise to encrustation, or it is carbonate-undersaturated (SI<0) in which case it is acidic, contains aggressive carbonic acid and is therefore corrosive and not only dissolves carbonate

Fig. 5 Box-whisker diagram of the molar calcium/magnesium ratio of the Kabul Basin groundwater in 2004. Symbol legend: *square* refers to the mean, x is equivalent to 1 and 99% values, *dash* refers to minimum and maximum values

the waters are at the saturation point or slightly oversaturated (Fig. 6). This is a consequence of the equilibrium with carbonate minerals which clearly must be present in significant quantities in the aquifer matrix. The oversaturation also explains the presence of consolidated gravel beds (conglomerates) at the base of the aquifer (Lataband Series, see part I of this study, Houben et al. 2008). Tests with dilute hydrochloric acid on conglomerate samples supplied by the Faculty of Geosciences, Kabul University showed that the cement of the conglomerate indeed consists of calcite. The redox potential can be used to infer the redox state of the water, i.e. whether the water is oxidising or

but also attacks metals. Equilibrium calculations with

PHREEQC-2 (Parkhurst and Appelo 1999) showed that



Fig. 6 Box-whisker diagram of the saturation index (SI) for calcite and dolomite of groundwater in the Kabul Basin in 2004. SI>0 indicates water is oversaturated, mineral phase can precipitate; SI < 0 means that water is undersaturated, mineral phase can dissolve. Symbol legend: *square* refers to the mean, *x* is equivalent to 1 and 99% values, *dash* refers to minimum and maximum values

reducing. A large number of chemical reactions of the water are dependent on this state. Because of the technical complexities involved in the measurement, and the fact that the measured potential is actually a mixed potential of various redox reactions taking place in parallel in the water, the measured values can only be used as a rough guide. Values measured in the Kabul Basin in 2004 reveal a balanced distribution around an average value of approximately 535 mV (Fig. 7). The samples therefore lie in the weakly oxidising or oxygen and nitrate depleting zone. In this zone, ammonium can be oxidised to nitrate. Reduction of manganese oxides is possible whilst the reduction of iron oxides and sulphates to dissolved iron and respectively sulphide is excluded.

Oxygen enters groundwater in dissolved form as a result of exchange with the atmosphere or soil gas. As a result, the highest concentrations usually occur in the upper parts of the groundwater column. Oxygen is the strongest naturally occurring oxidant in groundwater. It is therefore the first to be consumed during the (microbial) decomposition of organic contaminants (e.g. sewage) in accordance with Eq. 1. As already indicated by the redox measurements, the samples lie in the weakly oxidising zone. As a result, concentrations of dissolved oxygen are on average in the low mg/l range (Fig. 8). The temperaturedependent saturation state of the groundwater for oxygen was calculated from its measured concentrations (Fig. 8). Although the samples collected from the sampled wells must generally have come from shallow groundwater, less than 25% of all of the samples have oxygen saturations above 50%. The mean value is actually less than 20%. This strongly indicates the presence of oxygen depleting processes taking place in shallow groundwater.

The nitrogen species nitrate, nitrite and ammonium are very significant for the overall assessment of drinking water hygiene. The distribution of each of the species is



Fig. 7 Box-whisker diagram of Eh (redox potential) of the Kabul Basin groundwater in 2004. Symbol legend: *square* refers to the mean, x is equivalent to 1 and 99% values, *dash* refers to minimum and maximum values

also a good indicator of the redox environment of the groundwater. Nitrate indicates oxic conditions, whilst ammonium reveals reducing conditions. Nitrite is a byproduct generated at the start of nitrate reduction. Whereas the over-fertilisation of soils in Europe has given rise to the strong nitrate contamination of groundwater in many parts, the source of nitrogen in the Kabul Basin is found in the sewage. Nitrogen in sewage is largely in the form of urea which is readily converted into ammonium (Eq. 2a), probably already in the latrine. However, in the presence of oxygen, ammonium oxidises rapidly to nitrate (Eq. 2b). The ammonium concentrations measured as part of this study were so low that they barely had any impact on drinking water hygiene: approximately 45% of the samples were even below the detectable limit of 0.01 mg/l.

$$CO(NH_2)_2 + H^+ + 2 H_2O \Leftrightarrow 2 NH_4^+ + HCO_3^-$$
(2a)

$$NH_4^+ + 2 O_2 \Leftrightarrow NO_3^- + 2 H^+ + H_2O \tag{2b}$$

However, most of the samples showed considerable nitrate concentrations (Fig. 9). The nitrification of the ammonium (Eq. 2b) thus probably already takes place in the latrine and the unsaturated zone and only to a lesser extent in shallow groundwater. The measured redox potentials support the probability of this reaction.

The oxygen-consuming processes of nitrification and oxygenation of dissolved organic matter from sewage explain why the groundwater sampled in the Kabul Basin shows clear signs of oxygen depletion despite its near surface position. The acid generated during these reactions has almost no effect on the pH because of the considerable buffer capacity of the groundwater.

Nitrate is a very important drinking water hygiene parameter because concentrations above the WHO limit of 50 mg/l can lead to the formation of toxic nitrosamines via nitrite. This represents a considerable risk particularly to young children. Nitrate is reduced by bacteria in the stomach to nitrite which can irreversibly displace the oxygen bound to red blood cells in small children and infants. The children therefore suffer from a lack of oxygen and can even suffocate in extreme cases ("blue baby disease", haemaglobulinanaemia).

Since 42% of the samples exceed the limit, considerably in some cases (Fig. 9), it is possible that nitrate (alongside the microbial contamination) is one of the causes of the high infant mortality rate. Wells with excessive nitrate concentrations should no longer be used to supply drinking water. In 1996, 32.5% of all handpumped wells already exceeded a nitrate concentration of 45 mg/l (Timmins: in Banks and Soldal 2002). Because of its much higher toxicity, the drinking water limit for nitrite at 0.2 mg/l is much lower than the limit for nitrate. Because the groundwater in the Kabul Basin is oxidising almost throughout, albeit weakly, it is rare for nitrate to be



Fig. 8 Box-whisker diagrams of dissolved oxygen concentration and oxygen saturation in groundwater of the Kabul Basin in 2004. Symbol legend: square refers to the mean, x is equivalent to 1 and 99% values, dash refers to minimum and maximum values

reduced to nitrite. This is also indicated by the measured redox potentials and the fact that only 14 of 186 samples have nitrite concentrations above 0.2 mg/l. There is no correlation between raised nitrite levels and nitrate concentrations.

Phosphate is an essential trace element for the growth of fauna and flora. Because of its very high charge density, phosphate molecules are absorbed strongly in soils so that groundwaters frequently only have low values. Iron oxides are particularly good sorbers. Such limiting phenomena also appear to be present in the waters of the Kabul Basin because the phosphate concentrations in the groundwater are very low despite the obvious inflow of domestic sewage and the associated phosphate contamina-



Fig. 9 Box-Whisker diagram of nitrate concentration in ground-water of the Kabul Basin in 2004. Symbol legend: *square* refers to the mean, x is equivalent to 1 and 99% values, *dash* refers to minimum and maximum values

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tions. Phosphate is therefore not considered to be a risk to drinking water here.

Iron and manganese have similar geochemical behaviour and can therefore be discussed jointly here. In their oxidised forms (ferric iron, Fe(III) and manganic manganese, Mn(III, IV)) they form solid oxides. These are dissolved under low redox potential conditions as reduced soluble species ferrous iron (Fe^{2+}) and manganous manganese (Mn^{2+}) . Because of their tendency to oxidise and precipitate when they come into contact with air-which can block wells and pipes ("incrustation") and discolour clothing-the levels for ferrous iron and manganese are restricted even though they are not actually harmful to humans. The redox conditions of the groundwater in the Kabul Basin described above indicate that practically no iron can be mobilised from the aquifer at the measured redox potentials. The dissolved concentrations are therefore very low and very rarely exceed the limits. The redox potentials in the Kabul Basin cover the range of manganese oxide reduction and thus the mobilisation of manganese should be possible. However, the measured concentrations are very low and only rarely exceed the limits. This is probably due to the lack of manganese oxides in the aquifer. Final clarification of this finding requires geochemical analysis of the solid aquifer matrix.

Sulphate is a major constituent of groundwater. It is relatively mobile in groundwater because it is hardly affected by sorption. The limiting phase can again be gypsum if the dissolution equilibrium is exceeded. Raised concentrations are undesirable for various reasons: gypsum can precipitate when sulphate-rich water is heated and therefore block water boilers for instance. High sulphate concentrations also have a laxative effect although the human body can develop a tolerance to concentrations up to approx. 500 mg/l. Seventeen percent of the samples from the Kabul Basin exceeded the limit, considerably in some cases (Fig. 10). Because the loss of body fluid associated



Fig. 10 Box-Whisker diagram of sulphate concentrations in groundwater of the Kabul Basin in 2004. Symbol legend: *square* refers to the mean, x is equivalent to 1 and 99% values, *dash* refers to minimum and maximum values

with the laxative effect can be dangerous for children in particular, the wells with strong sulphate contamination should no longer be used for human consumption. These wells are usually the same as the wells with elevated salinity anyway. A possible source or sink for sulphate could be gypsum (CaSO₄·2H₂O) or anhydrite (CaSO₄) from the aquifer matrix. However, as equilibrium calculations with PHREEQC-2 revealed, the waters do not reach the saturation indices for gypsum anhydrite—with one exception—which means that these mineral phases cannot be precipitated out of the water (Fig. 10). Sulphate could therefore originate in part from non-mineral sources, e.g. sewage.

Sulphate is converted by reduction to sulphide or hydrogen sulphide (H₂S) under very low redox potentials << 0 mV. This is very easy to identify even at very low concentrations because of its characteristic "rotten egg"

smell. Matching very low redox potentials were not recorded in this study. Although sulphide and hydrogen sulphide were not analysed as part of the sampling campaign discussed here, no sulphate-free samples were encountered, as would be the case with classic sulphatereducing waters. In addition, no scent of "rotten eggs" was noticed in the field. Given these findings, and the redox potential, it is clear that sulphate reduction does not play a role in the Kabul Basin groundwaters—at least not with respect to shallow groundwaters.

The groundwater in the Kabul Basin has sodium and chloride concentrations whose median values are much higher than those of natural waters in humid regions (Fig. 11). Because sea spray and de-icing salt can be ruled out here as sources, the salt concentrations measured here are probably the result of evaporation. Climatic data covering the Kabul Basin (see part I of this study, Houben et al. 2008) support this theory. However, some influence from sewage cannot be excluded. Twenty-six of the investigated samples have excess levels of sodium, whilst 25 samples have excess amounts of chloride, i.e. approx. 14% of all samples (Fig. 11). The two groups are congruent with only one exception. Some of the concentrations of each of the ions exceed 1,000 mg/l. Water with these concentrations is unsuitable for human consumption, as well as being corrosive.

With regard to spatial distribution, the cluster of raised Na^+ and/or Cl^- concentrations in the area to the west of the Kabul airport stands out from the rest. This area previously was a swampy zone with a shallow water table which has dried out in recent years as a result of the drought. This has caused the dissolved salts to precipitate and become concentrated in the top soil. Salts can also become concentrated by the capillary rise of shallow groundwater to the surface.

The element boron usually occurs in groundwater in the form of the anion borate (BO_2) . Because its toxicity to humans is fairly low, it has a relatively high (European)



Fig. 11 Box-whisker diagram of sodium and chloride concentrations in the groundwater of the Kabul Basin in 2004. Symbol legend: *square* refers to the mean, *x* is equivalent to 1 and 99% values, *dash* refers to minimum and maximum values

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limit of 1 mg/l (WHO 0.5 mg/l B = approx. 2 mg/l BO₂). Boron is an essential trace element for fauna and flora. However, high concentrations in irrigation water can negatively affect the growth of plants. It can also become toxic for fish at higher concentrations in surface waters (10–300 mg/l). Borate is a highly mobile ion. Due to the high solubility of boron minerals, borate can spread widely because it precipitates only under extremely evaporative environments. The spread is prevented to a minor degree by sorption, e.g. on iron oxide minerals.

Borate can be derived from various sources:

- Many detergents contain sodium perborate (NaBO₂ (OH)₂·3 H₂O) as agent for oxidation. Because borate is formed by the release of hydrogen peroxide from the perborate, it is frequently used as an indicator for domestic sewage which frequently shows concentrations of 0.1 mg/l boron (= 0.4 mg/l borate)
- Borate becomes enriched in the residual solutions during evaporation because boron minerals are highly soluble and precipitate only very late in the evaporation sequence
- Volcanic gases or volcanogenic thermal springs
- Oilfield water
- Weathering of boron-bearing minerals, e.g. tourmaline, biotite, amphibolite
- Agricultural fertiliser (0.01–0.5 wt% boron).

The first two processes mentioned above could take place in the Kabul Basin. Given the large population and the lack of any sewers or sewage treatment, it is probable that the boron represents contamination from domestic sewage. Because the use of modern detergents is much lower in Kabul than in the developed world, the concentrations in the sewage in Kabul are probably quite small. However, the latest figures measured in the groundwater of the Kabul Basin are on average almost one order of magnitude above the figures for sewage in central Europe (Fig. 12). They therefore almost reach the average figure for sea water of 4-5 mg/l. This means that there is either another natural source of boron or that the boron input has been concentrated by "recycling", i.e. being pumped up in hand-pumped wells and then percolating back down again with the sewage. The enrichment of borate here is probably due to evaporative processes. Potential evapotranspiration in the Kabul Basin significantly exceeds precipitation throughout the year (see part I of this study, Houben et al. 2008). The borate concentrations in the few "pristine" springs and karezes (underground water channels) sampled outside the city, which are not affected by sewage water nor much evaporation, are accordingly lower (< 0.5 mg/l).

A notable feature of the water samples from the Kabul Basin is that only a few samples lie below the limit of 0.5 mg/l B or 2 mg/l BO₂ (Fig. 12). The US Geological Survey sampling survey by Broshears et al. (2005) revealed a similar picture although the values were slightly lower. The values in the urban areas are, however, higher than in the surrounding more rural area. The molar



Fig. 12 Box-Whisker diagram of borate concentrations in the groundwater of the Kabul Basin in 2004. Symbol legend: *square* refers to the mean, x is equivalent to 1 and 99% values, *dash* refers to minimum and maximum values

ratio of boron (borate) to chlorine (chloride) can be used as an indicator to determine the origin of the water. According to Davies and De Wiest (1967), sea water and surface waters have a B/Cl ratio of 0.0002, whilst oilfield waters have a ratio of 0.02, and volcanogenic thermal waters a ratio of 0.1. The groundwater in the Kabul Basin has an average which lies between the two latter values. The values therefore show an enrichment in boron compared to chloride as a result of the evaporative environment. The same applies to bromide. In seawater and most groundwaters, the molar chloride/bromide ratio is around 300:1. Because bromide salts are even more soluble than those of chloride, chloride precipitates out first, usually in the form of sodium chloride (NaCl). This enriches the residual solution with bromide. The molar Cl/ Br ratio of the Kabul waters lies around 1,000:1 and is therefore much higher than for seawater and normal groundwaters.

Despite the presence of crystalline rocks in the surrounding area (see part I of this study, Houben et al. 2008), the aquifers of the Kabul Basin hardly contain or release any fluoride. The concentration in groundwater exceeds the limit of 1.5 mg/l slightly only in one case. Fluoride is therefore of no relevance here for drinking water hygiene.

Water with a low pH can dissolve the solid constituents of soil and/or desorb metal ion sorbed on the soil matrix. Iron oxide and manganese oxide can absorb large amounts of heavy metals and metalloids. Well-known examples are nickel and arsenic. These trace elements can be mobilised in groundwater by dissolution under acidic conditions. Because of the redox-related stability of the iron oxides and manganese oxides in the aquifers, the nickel concentrations are very low. Only one sample exceeded the limit of 0.05 mg/l. Most of the samples are well below the limit and some even below the detection limit. Concentrations of nickel, zinc, copper and cobalt of the vast majority of all samples are far below the drinking water limits and often even below the detection limits. The drinking water limits are only exceeded slightly for very few samples. The same applies for arsenic which is subject to a low drinking water limit of 0.01 mg/l due to its high toxicity. Of the 167 analysed samples, only three showed concentrations just above the drinking water limits. All analyses for lead and cadmium yielded values below the detection limit of 0.005 and 0.03 mg/l, respectively.

Microbiology

Pathogenic microorgansims, i.e. illness-causing bacteria and viruses can enter groundwater as a result of anthropogenic influences, e.g. emissions of faeces, sewage and toxins. Most of the diseases caused by contaminated groundwater are attributable to the input of such microorganisms. The bacterial contamination of aquifers almost always concerns faecal contamination. The most important intestinal inhabitant of warm-blooded creatures is the bacterium *Escherichia coli*. This bacterium can only multiply within the intestines of its host and has a limited lifetime outside of its natural habitat of 40–60 days. It is therefore a good indicator of recent faecal contamination.

Data from the US Geological Survey study showed the presence of coliform bacteria in 79 (73%) of 108 investigated samples (Broshears et al. 2005); 25 samples (ca. 23%) also showed *E. coli*. The US Geological Survey study also showed that microbial contamination also affects wells in the surrounding rural area of Kabul. Many of these cases are probably associated with inadequately sealed wells, in particular for shaft wells.

Banks and Soldal (2002) present a summary of the 1996 results from Timmins as part of the "Action Contre La Faim" programme which investigated 1,400 wells in the Kabul Basin (Table 1). According to this study around 45% of all wells with hand pumps were contaminated with *E. coli*. This number is even higher than the US Geological Survey finding. The considerably higher contamination of the shaft wells highlights the importance of proper well sealing for drinking water hygiene. It is also interesting that the contamination of the water supplied via the distribution networks is no better than water from the hand-pumped wells (Banks and Soldal

Table 1 *E. coli* contamination in Kabul's domestic water in 1996 (n=1,400, data from Timmins in Banks and Soldal 2002)

Source	E. coli		
	> 5 per 100 ml	> 100 per 100 ml % of sources	> 500 per 100 ml
Wells with hand pumps	45.2	11.1	1.3
Open wells	76.5	31.9	4.2
Distribution networks	49.0	15.7	1.96

2002). The pipelines are probably old, badly maintained and thus leaky.

The infant mortality in 2006 according to UNICEF (2008) of 165 children per 1,000 under the age of 1 year and 257 children per 1,000 up to the age of five is therefore probably largely attributable to the poor drinking water quality in Kabul. The illnesses responsible for this mortality are mainly diarrhoea diseases.

The high permeability of the main aquifers in the Kabul Basin (see part I, Houben et al. 2008) causes fast spreading and low retention of micro-organisms. A crucial factor in retaining the microbiological contamination from the countless drainage pits are the loess and loess-loam beds near the ground surface which have a particularly good filtration capacity because of their fine-grained matrix. Special attention should be paid to ensuring that the loess beds are not penetrated when constructing drainage pits and that drainage pits are not dug in areas where there is no loess cover. Care should also be taken to ensure that wells are constructed at an adequate distance to percolation pipes and sewage channels.

Comparison to historical data

A comparison of the results of the water samples analysed in this study with historical data could show how the population increase and the drought have affected water quality. However, there are no data at all for the 1979-2002 period because of the lengthy war and the civil conflicts. The data available consisted of hydrochemical maps of the Kabul Basin from Grebe et al. (1966) prepared as part of the "German Geological Mission in Afghanistan" conducted by BGR. The samples were analysed in the laboratory of the Afghan Geological Survey in Kabul which is where the original data were also archived-and lost. Analyses were carried out for chloride, sulphate, total hardness, carbonate hardness, calcium and magnesium hardness. The investigation at that time included 27 karezes, 346 shaft wells (shallow groundwater) and 10 pipe wells (deeper groundwater). The values were presented in maps as bar charts. Precise co-ordinates and numbers of the measuring points were not documented. Because the original data were lost as a result of the war, the values had to be read off from the bar charts using a ruler. This method of course led to some unavoidable inaccuracies.

However, the results of the past investigations differ in part very significantly from the groundwater analysed in 2004 by BGR and US Geological Survey. Differences include:

- Increase in salt concentration
- Considerable increase in calcium and magnesium (hardness)
- Considerable increase in nitrate
- Clear increase in sulphate
- Raised sodium and chloride concentrations
- Greater contamination with faecal bacteria.

These differences can be largely explained by contamination with sewage although climatic influences may also play some part.

The recent and the historical data have the following significant similarities:

- Neutral to weak basic pH
- Low Ca/Mg ratios
- Low iron concentrations
- Low (heavy) metal concentrations
- Similar ammonium and nitrite concentrations.

This indicates that the redox environment has not changed much despite the greater contamination with oxygen-depleting sewage. The constant pH reveals that the buffer capacity of the groundwater, and the carbonate content of the aquifer in particular, has been large enough to completely buffer even major input of acid arising from nitrification.

Discussion

The recent water quality data obtained from this study allow a reaction sequence to be derived by comparison with the historical quality data, which can be used to explain the genesis of the hydrochemistry (Fig. 13). Of critical importance here is the sewage which has a massive impact on the natural groundwater quality. The main constituents of sewage are biomass and salts such as ammonium from the breakdown of organic nitrogen compounds (e.g. urea). Biomass primarily arises from faeces (80%), whilst the nitrogen salts primarily come from urine (90%).

The first step involves the oxidation of sewage ammonium to nitrate (Eq. 2b) whilst the biomass becomes mineralised (Eq. 1). This depletes the dissolved oxygen and releases acids which in due course dissolve solid carbonates from the aquifer matrix with a subsequent increase in hardness. Evidence for these reactions includes the low oxygen saturation of the shallow groundwater and the absence of ammonium. Contamination by sewage is not high enough, however, to cause complete oxygen depletion. The acid is subsequently buffered by reaction with the solid (calcium) carbonate from the aquifer matrix (Eq. 3) which causes a significant increase in the total hardness of the water. There is therefore hardly any change in the pH.

$$H^+ + CaCO_3 \leftrightarrow HCO_3^- + Ca^{2+} \tag{3}$$

Humans excrete around 14 g (= 1.0 mol) nitrogen per day in urine in the form of 30 g urea (CO(NH₂)₂). Complete nitrification of the resulting ammonium according to (Eq. 2a) gives rise to approx. 62 g nitrate and 2 mol acid. Buffering the latter requires 2 mol calcium carbonate in accordance with (Eq. 3)—which corresponds to a mass of around 200 g. Given this very high value, one also needs to take into consideration the fact that a small amount of nitrogen at least in the drainage pit is not converted into ammonium but into gaseous ammonia. This escapes into the atmosphere. In addition, humans also excrete 30– 60 mmol/l (2.9–5.8 g) sulphate every day in their urine.



Fig. 13 Simplified diagram showing the anthropogenic impact on groundwater quality associated with the chemical processes arising from sewage contamination in Kabul

These figures can be used to balance the emissions of the current population of 3.5 million people. The fact that the inhabitants include very large numbers of children needs to be taken into consideration because they excrete smaller amounts of minerals because of their lower body weight. If one assumes daily excretion of 20 g urea (= 41 g nitrate) and 3 g sulphate, the total emissions are therefore

52,400 t/a nitrate 3,800 t/a sulphate

It is not currently possible to estimate the degree to which processes which break down nitrate reduce the nitrate pollution. The most probable denitrification pathway is heterotrophic denitrification by organic matter (Eq. 4).

$$5''CH_2O'' + 4NO_3^- \leftrightarrow 2N_2 + 4HCO_3^- + CO_2 + 3H_2O$$
(4)

This process will only commence after most of the oxygen has been consumed. Equation (4) could explain the removal of larger amounts of dissolved organic carbon from the water by degradation of the faecal biomass. Since organic carbon is converted to inorganic heterotrophic denitrification, this would at the same time lead to extra hardening of the water (Eq. 4). Nitrate nitrogen is

transformed into nitrogen gas (N_2) by this process which largely escapes to soil gas and finally into the atmosphere. Usually the amount of biomass (faecal biomass and kitchen slops) is higher than the amount of organic carbon consumed by heterotrophic denitrification. Therefore some organic carbon is probably released into soil and/or groundwater where it consumes oxygen. The overall processes depicted in Fig. 14 closely resemble the processes occurring in sewage treatment plants.

Assessing the significance of contamination in the Kabul Basin, it is prudent to look at the main material flows, at least qualitatively (Fig. 14). The closed system of the Kabul Basin as an intra-montane basin, allows such a balance to be delimited. The Logar, Kabul and Paghman rivers only transport a minor amount of mineralisation with them when they enter the basin. In addition to seepage from the rivers, there is some infiltration at the foot of slopes. The mineralisation of the recharged water increases slightly more as a result of water-rock-interactions within the aquifer. The large increase in the number of inhabitants in Kabul gives rise to a considerable increase in the material load because of the disposal of sewage directly into the groundwater. The reaction of the sewage with the soil and the aquifers also cause additional changes to the water quality.

The enrichment in the salt load is exacerbated further by the strong evaporation and the import of food, drinks, construction materials and fuel and the associated net mineral imports. Quantitatively, the only significant



Fig. 14 Schematic diagram of material flows in the groundwater of the Kabul Basin

discharge route for pollutants is Kabul River—and/or the groundwater—at the basin outlet at Tangi Gharu. Discharge in times of drought is very low which concentrates mineralisation further. Inhabitants also continue to extract groundwater and infiltrate only smaller amounts back because of the evaporation losses. This lowers the water levels and reduces the amount of stored water. Because most of the infiltrating water is sewage, this must give rise to a strong accumulation of salts particularly when they are recycled many times.

Data from the US Geological Survey study (Broshears et al. 2005) has now made hydrochemical analysis data available on the rural area surrounding Kabul. Comparisons are necessary because these areas have basically the same geology as the urban areas but have lower population densities and land use. In simple terms, the rural areas have quasi-geogenic groundwater qualities because the sparse habitation and low levels of fertiliser use mean that they have suffered virtually no anthropogenic impact. Only samples which lay outside of the urban area investigated by BGR were selected from the US Geological Survey data set (n=62). Figure 15 summarises the difference between the urban areas (BGR samples) and the rural surroundings (selected US Geological Survey samples).

This reveals that the concentration of the sewagerelated contaminants nitrate and sulphate are almost twice as high in the urban area as in the rural areas. This is also associated with major differences in the concentrations of the hardness-forming ions calcium, magnesium and bicarbonate which are much higher in the urban areas. This provides excellent confirmation of the theory



Fig. 15 Box-whisker diagram of concentrations of nitrate, sulphate, calcium/magnesium and bicarbonate in groundwater of the Kabul Basin in 2004 in Kabul city (BGR data set) and the surrounding rural areas (USGS data by Broshears et al. 2005). Symbol legend: *square* refers to the mean, x is equivalent to 1 and 99% values, *dash* refers to minimum and maximum values

presented in Fig. 13 which proposes that the acid arising from the mineralisation of urea and the organic matter in the sewage is buffered by the reaction with carbonates. Magnesium plays an extraordinarily important role here as well.

Conclusions

Shallow groundwater is currently the most important drinking water resource for the inhabitants of Kabul. It is pumped up by countless hand-pumped wells throughout the city which account for 80% of all users. Because there is no systematic sewage treatment or refuse collection, the shallow groundwater is affected by considerable contamination and the associated hygiene problems. The high mortality rate of infants is probably partially due to the contaminated groundwater.

A groundwater sampling campaign conducted in 2004 throughout the city of Kabul involved the extraction and analysis of around 190 water samples. The shallow groundwater generally has a weakly oxidising redox environment with oxygen depletion, probably caused by sewage water. Together with the neutral pH, this prevents the mobilisation of trace metals. Local groundwater salinisation has been identified e.g. in the former swamps to the west of the airport.

Natural processes which have an effect on the quality of the groundwater are:

- Interaction of groundwater with carbonate rocks causing hardening of the water throughout the area: this hardness buffers acidic contaminants, e.g. from the oxidation of sewage, and also gives rise to a high encrustation potential for wells, pipes and household appliances.
- Strong evaporation associated with the mainly negative hydrological balance in the Kabul Basin: evaporating water leaves behind dissolved salts which become concentrated. This raises the salt concentration as well as the concentrations of some problematic constituents, e.g. borates. The recent drought and the import of material, e.g. food and construction materials, considerably worsens this problem.

Considerable anthropogenic emissions are identifiable in the urban area which have a serious impact on the natural groundwater quality, e.g. through massive input of nutrients and bacteria from sewage and uncontrolled waste disposal. Sewage-related pollution is clearly identifiable compared to the data from the 1960s. The concentrations of nutrients and salts have increased accordingly. Denitrification consumes large amounts of faecal biomass. The acid input arising from the chemical transformation processes of the sewage are buffered by the dissolved carbonates of the water, but this in turn increases the hardness of the water further.

The aquifers in the Kabul Basin present no barrier to the spread of contaminants because of their sandy to gravely composition and the associated good permeabilities. In contrast, shallow loess beds are invaluable in this respect particularly for the retention of faecal bacteria from the countless cess pits. Protection of the loess beds

should be given a high priority. The information acquired by this study is an important basis for practical recommendations for action and the intended future regulated management of groundwater resources in the Kabul Basin. The full report of the hydrochemical BGR campaign can be downloaded free of charge from the BGR homepage (BGR 2005). The report also includes more information on several parameters not discussed here and some maps on the spatial distribution of hydrochemical parameters in the Kabul Basin.

Outlook

The major contamination of the Kabul Basin groundwater with dissolved minerals can naturally only be reduced by a wet period lasting several years which flushes out the minerals from the aquifer. The mean residence time of groundwater in the basin - which is yet unknown - needs to be considered in this regard.

The problem can be ameliorated by implementing urban planning and/or technical measures:

- Regulated urban planning
- Regulated refuse disposal/collection in the urban area and proper disposal
- Centralised and/or decentralised water supply (with treatment)
- Centralised and/or decentralised sewage treatment
- Sale of water from tankers

Because of the size of the city, the frequent uncontrolled building, and the widespread poverty, it is unrealistic to upgrade centralised water supply and disposal at a large scale. Decentralised solutions with the supply of several blocks from deep wells and sewage disposal with small downstream treatment plants are feasible in some urban districts at least. Given the probability of the repeated occurrence of droughts, a long-term solution worthy of consideration should be long-distance water supply from rainy areas in the north (e.g. from Salang).

Short-term measures will only have a limited effect. These include shutting down the particularly strongly contaminated wells. Attention should also be given to the proper construction of drainage pits. They should never be constructed in the immediate vicinity of wells or in areas where there is no loess cover. They should also never be dug so deeply that they penetrate the base of the loess cover.

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