Assessing the extent of induced leakage to an urban aquifer using environmental tracers: an example from Bishkek, capital of Kyrgyzstan, Central Asia

Brian L. Morris · W. George Darling · Daren C. Gooddy · Rafael G. Litvak · Ilka Neumann · Ekaterina J. Nemaltseva · Inna Poddubnaia

Abstract A groundwater residence time study of the deep fluvioglacial aquifer supplying Bishkek, capital of Kyrgyzstan, has found evidence of deep infiltration of recent recharge both in the main periurban wellfield and below the city. Commonly-employed hydrochemical markers detected urban influence in the city-centre to depths of 65–100 m, but gave no indication of the important role of induced river/canal bed leakage, either upgradient in the periurban wellfield or within the city. This was revealed by O and H stable isotope measurements, which showed that local rainfall/snowfall play little part in the aquifer water balance. More remarkably, the universal detection of CFCs and SF_6, including in boreholes with 140–220 m deep upper screens, demonstrated that induced leakage of water just a few decades old had penetrated much deeper into the aquifer system than other hydrochemical markers indicated. A two-dimensional flow model set up to test whether such deep pumping-induced leakage could occur below the periurban wellfield confirmed its feasibility. The results imply vertical infiltration rates of 5–10 m/year and demonstrate that in this not-uncommon intergranular aquifer setting, deep boreholes with deep screen settings do not necessarily abstract old water. Hence, there are major implications for urban groundwater management and protection in such settings.

Résumé L'analyse du temps de résidence des eaux souterraines dans un aquifère fluvial profond, d'origine glaciaire, qui alimente en eau Bishek, la capitale de Kyrgyzstan a mis en évidence une recharge récente tant dans le captage en eau que sous la ville même. Les traceurs chimiques ont indiqué l'influence urbaine dans le centre de la ville, à une profondeur de 65–100 m, mais ils n'ont pas mis en évidence le rôle important de l'alimentation induite par la couche du fleuve, tant en amont, dans le captage que en aval, dans la ville. Ces effets ont été relevés par des isotopes stables, comme O et h qui ont montré l'influence récente des précipitations dans le bilan hydrique de l'aquifère. De plus, la détection universelle de CFC et de SF6, y compris dans les forages ayant une profondeur de 140–220 m, montre que l'alimentation en eau induite de plusieurs décennies a pénétré à des profondeurs plus grandes que celles indiqués par des traceurs chimiques. Les possibilités d'une drainance verticale induite par les pompages dans le puits profonds du captage ont été vérifiées par un modèle bidimensionnel d'écoulement. Les résultats de la modélisation ont conduit à une infiltration verticale de 5–10 m/an et ont démontré aussi que l'eau extraite par des puits profonds dans un aquifère granulaire n'est pas nécessairement d'age ancienne. Il s'agit donc des implications majeures concernant la gestion et la protection des captages urbaines en eaux souterraines

Resumen Un estudio sobre el tiempo de residencia del agua subterránea, en un acuífero fluvioglacial profundo que abastece a Bishkek, capital de Kyrgyzstan, ha encontrado evidencias de infiltración profunda a partir de recarga reciente, tanto en el campo de pozos de las afueras de la ciudad, como también por debajo de la ciudad. Los indicadores hidroquímicos comúnmente usados, detectaron influencia urbana en el centro de la ciudad hasta profundidades de 65–100 m, pero no dieron indicación del papel importante del goteo inducido en el lecho del canal/río, tanto aguas arriba en el campo de pozos de los suburbios, como también dentro de la ciudad. Esto se reveló mediante mediciones de isótopos estables de O y H, las cuales mostraron que las precipitaciones/nevadas de tipo local, tienen una pequeña contribución en el balance de agua del acuífero. De manera más notoria, la detección universal de CFCs y SF6, incluidos en las rejillas superiores de pozos profundos con 140–220 m de profundidad, demostraron que un goteo inducido de agua, de solo unas pocas décadas de antigüedad, ha penetrado mucho más profundo dentro del sistema acuífero, de lo que los otros marcadores hidroquímicos indicaban. Un

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B. L. Morris (✉) · W. George Darling · D. C. Gooddy · I. Neumann
British Geological Survey, Maclean Building,
Crowmarsh Gifford, Wallingford, Oxon, OX10 8BB United Kingdom
e-mail: blm@bgs.ac.uk
Tel.: +44-1491-838800
Fax: +44-1491-692345

R. G. Litvak · E. J. Nemaltseva · I. Poddubnaia
Kyrgyz Research Institute of Irrigation,
4a Toktonalieva St, Bishkek, 720055 Kyrgyzstan
e-mail: lit1@elcat.kg

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modelo bidimensional de flujo, realizado para probar si el goteo inducido—bombeo profundo podía suceder debajo del campo de pozos suburbano, confirmó su factibilidad. Los resultados implican tasas de infiltración vertical de 5 a 10 m/año, y demuestran que los pozos profundos con tramos de rejilla también profundos, no necesariamente extraen aguas antiguas, en estos ambientes acuíferos con porosidad intergranular. Por lo tanto, hay implicaciones importantes para la gestión y protección en zonas urbanas, y para esos ambientes de las aguas subterráneas.

Keywords Urban groundwater · Kyrgyzstan · Central Asia · Groundwater age · Groundwater recharge/water budget · Groundwater management · CFCs · SF_6 · Stable isotopes

Introduction

By 2030 it is estimated that more than 60% of the world's predicted population of 8,400 million will live in towns or cities (UNCHS 1997). Most urban population growth is now concentrated in the developing world, and many of these cities are groundwater-dependent; over half of the world's 23 megacities rely upon, or make significant use of, groundwater (Morris et al. 2003). Its role in urban development is especially critical where key aquifers are located below the city or in the immediate periurban zone.

In comparison with surface water catchments supplying cities, many urban aquifers remain under-studied and under-protected. Typically the incremental and dispersed nature of groundwater development, much of which is in the private sector with numerous individual wellowners, is an important factor. Such piecemeal development does not provide opportunities or impetus for the water resource studies that are a prerequisite to a capital-intensive scheme like a supply reservoir and dam. There is also commonly a sense that usage of urban/periurban aquifers is a relatively transient phase pending development of more distant pristine sources, once the necessary capital investment can be found.

However, urban planners are finding it increasingly difficult to replace a degraded urban aquifer by alternative water sources from the hinterland, where resources may already be fully utilised for agricultural or ecological purposes (Burke and Moench 2000). Sustainability principles, agreed to by more than 150 countries since the 1992 Earth Summit manifesto mean that in the future, a city fortunate enough to possess a significant urban aquifer resource can no longer regard it as a discardable asset, to be abandoned once dewatered or heavily contaminated. Added to this is an emerging awareness of the interdependence between the underlying aquifer system and the water infrastructure of a city, i.e. the pipe network and sanitation system (Lerner et al. 1990; Foster et al. 1993; Eiswirth 2001) and urban reaches of rivers (Grischek et al. 2001). Poor management, or more commonly absence of management, may, for instance, result in the same city experiencing drastically falling water levels during early expansion followed by groundwater flooding at later development stages (Morris et al. 2003).

There is accumulating evidence to show that recharge in urbanised areas is typically increased over the pre-urban condition (Lerner et al. 1990; Foster et al. 1993; Krothe et al. 2002), and several recent studies have shown penetration of urban recharge to depths ≥40 m (Table 1).

Such induced leakage of urban recharge to deeper horizons has aquifer sustainability implications: deep aquifer withdrawals may only be maintainable at the expense of raw water quality. This is an important topic for urban water resource management because deep aquifers are a common source of water for piped public supply in many groundwater-dependent cities.

A common scenario where a developing city overlies a major aquifer system is one of individually modest but cumulatively significant abstraction by private industrial,

Table 1 Examples of induced leakage of urban recharge under intensive abstraction conditions

City	Hydrogeological environment	Max. reported depth of induced urban recharge	Reference
Santa Cruz, Bolivia	Neogene alluvium; semi-unconfined to unconfined patchy multiaquifer	>90 m in the most intensely pumped area	BGS and SAGUAPAC, 1997; Morris et al. 2003
Moscow, Russia	Palaeozoic limestone; confined beneath variable cover, with recharge 'windows'	>50 m in recharge windows of c. 250 km^2 total area	Dzhamalov and Zlobina 2001
Sana'a, Yemen	Quaternary alluvium; unconfined	60 m below city to >100 m beneath periurban wastewater treatment ponds	Alderwish and Dottridge 1999
Caracas, Venezuela	Neogene alluvial and lacustrine sediments; patchy aquifer	>40 m	Seiler and Alvarado Rivas 1999
Nottingham, UK	Permo-Triassic sandstone at outcrop and below alluvium	30–40 m at urban multilevel research piezometers	Cronin et al. 2003
Birmingham, UK	Permo-Triassic sandstone at outcrop, below alluvium and confined below Triassic mudstones	50 m in unconfined sandstone, 91 m in the confined sandstone	Powell et al. 2003
		Inorganic and organic contamination detected generally above 135 mbgl	Rivett et al. 1990; Ford and Tellam 1993

commercial or domestic users from shallow-to-moderate depths. High-yield public supply boreholes generally tap moderate-to-deep horizons within the city (although peri-urban wellfields are more variable, depending on the hydrogeological setting and how rural the wellfield was at the original date of design/construction). Abstraction from both user types generates large vertical head gradients that, depending on the aquifer setting, can result in deep infiltration of urban recharge (Lawrence et al. 2000).

This paper describes a groundwater quality and residence time study of the aquifer system underlying the wholly groundwater-dependent city of Bishkek, Kyrgyzstan. While Bishkek (like many small-to-medium-size developing cities) lacks a master plan for groundwater management, modern hydrogeochemical techniques can be used to develop a model for the urban groundwater resource. This is a cost-effective preliminary to the large number of measurements of water levels etc. necessary to characterise physical models. The Bishkek study complements a study of Narayanganj (Bangladesh) as examples of how to develop technically and socio-economically appropriate guidelines for urban groundwater protection policies in developing cities (Morris et al. 2002).

Fig. 1 Location of Bishkek, capital of Kyrgyzstan, Central Asia

Background

Physical and hydrogeological setting

Bishkek, population approximately 800,000, lies on the northern flanks of the Alatau range of the Tien Shan mountains in northern Kyrgyzstan of which it is the capital city (Fig. 1). The city is 100% aquifer-dependent for potable, domestic, commercial and industrial water supplies which are provided by both intraurban and periurban wellfields.

The city's groundwater setting is hydrogeologically complex, with a laterally heterogeneous intergranular fluvioglacial/alluvial multi-aquifer system of Quaternary age that is in excess of 350 m thick in northern districts of the city. There is strong lateral and vertical variability but as a first approximation the system fines laterally northwards, over a distance of less than c. 10 km, from coarse clastic deposits composed of coalesced piedmont fans fronting the foothills into more stratified deep alluvial sediments forming an extensive plain to the north (Fig. 2).

Despite the semi-arid climate (10-year average 1979–1988 of 4,41 mm/a) there are potential opportunities for recharge additional to that from rainfall from two snow-melt rivers (the Ala Archa and the Ala Meddin) and

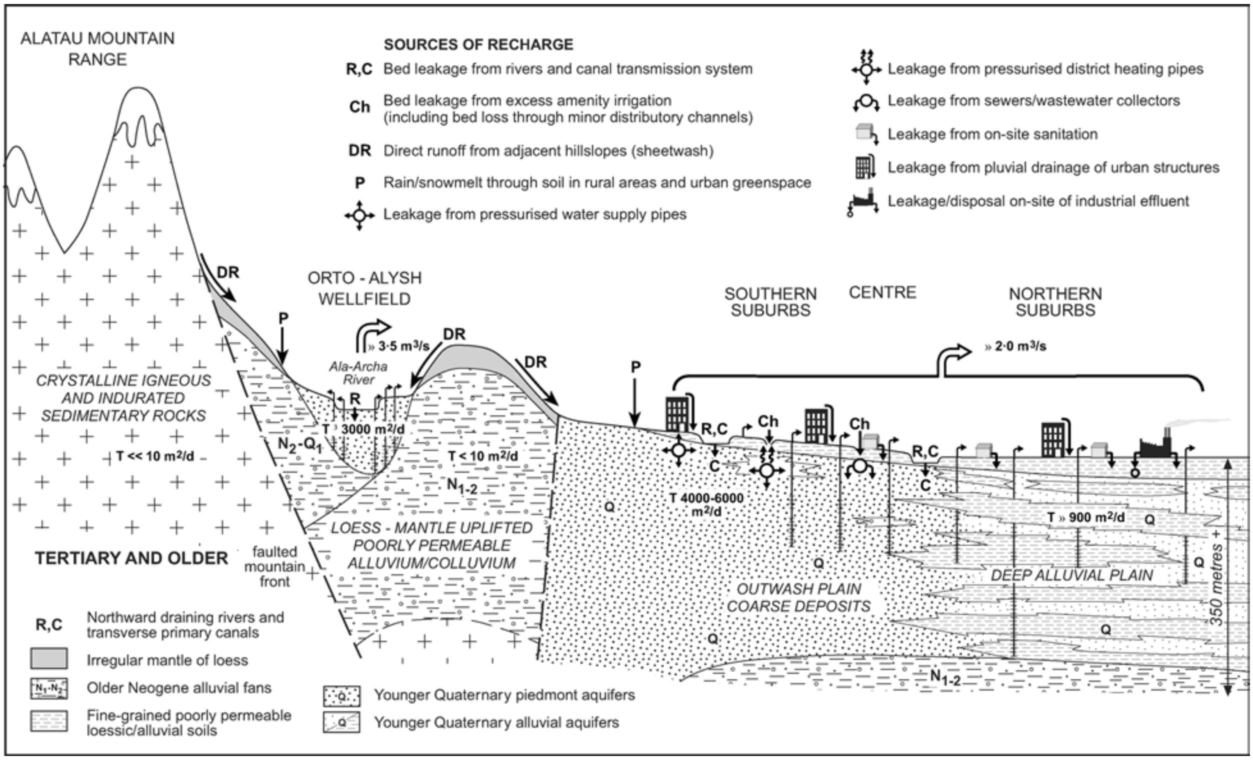

Fig. 2 Groundwater setting of Bishkek, Kyrgyzstan (sketch is not to scale, but extent from Orto Alysh to Northern suburbs is c. 18 km)

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associated canal systems draining the mountainous and winter-snowbound Alatau range. Hydraulic connection with surface flow across the coarse clastics of the piedmont and southern part of the outwash plain is likely as the aquifer system is unconfined.

More complex semi-confined conditions occur in the flatter northern part of the city where a thin but extensive surficial silty clay is present. Based on a combination of pumping test results and drilling returns, the aquifer system beneath the city proper has historically been divided into an upper, middle and lower aquifer. Although a tripartite division is employed in this paper (Fig. 3), more recent limited inspection of drilling logs suggests such a separation may be rather arbitrary, with the system probably better approximated as a thick and complex patchy aquifer (ÓDochartaigh et al. 2000).

Scope therefore exists for pumping-induced vertical leakage of potentially contaminated urban recharge to significant depths. This is especially likely in the southern parts of Bishkek where the coarseness of the piedmont clastic deposits and relative paucity of intervening low-permeability horizons favour strong vertical connectivity. The unconsolidated alluvial and fluvio-glacial deposits comprising this intergranular flow aquifer system have high transmissivities (900–6,000 m^2/d) and vertical permeabilities, although unmeasured, are likely to be large. Urban boreholes abstract water from widely different depths with uppermost screens ranging from 45 mbgl to more than 300 mbgl.

Groundwater development setting

A highly productive well field located only 8 km south of the city centre in a very localised periurban valley-fill provides up to 3.5 m^3/s or about two-thirds of the city's water demand, the balance coming from boreholes of various depths distributed throughout the city. The latter are screened extensively in the middle aquifer (typically >120 m intake depth), but the lower part of the upper aquifer (40–120 m) is also widely tapped.

The majority of abstraction boreholes are operated by the municipal water supply utility Bishkekvodokanal, which provides water for both domestic and industrial purposes. There are three separate reticulation systems for domestic water: cold water for potable use, hot water for non-potable use and hot water for district heating use, the last being a closed system which operates only during the winter. All come under the description 'public water supply'. Private urban water use is much less important both numerically and volumetrically; a small number of factories have private wells for potable or non-sensitive supply and there are also a few private domestic and municipal irrigation wells in seasonal use. Owner-operated boreholes for commercial premises, hospitals and large state administrative buildings appear to be insignificant.

Although there is a very extensive piped water infrastructure (pressurised drinking water and hot water mains, piped sewerage), widespread on-site sanitation (both latrine and septic tank) is practised in single/two-storey residential areas. Amenity irrigation of communal open space in residential areas is common, using both canalised surface water and pumped groundwater.

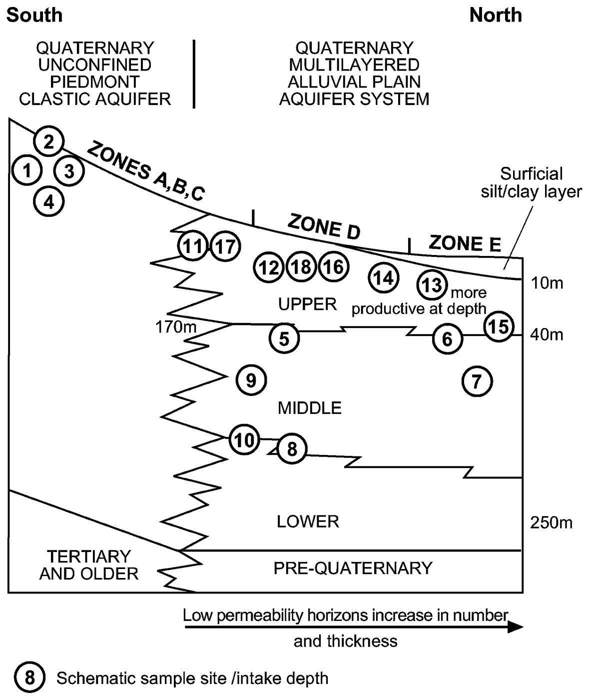

Fig. 3 Schematic section of hydrogeological system underlying Bishkek

Environmental tracers

Three main categories of environmental tracer were used in this study: hydrochemistry, stable isotopes, and age indicators. In an urban aquifer context, the distribution of nitrogen species and minor elements respectively can be illuminating in terms of the penetration of pollutants (e.g. Ford and Tellam 1994; Howard 2001; Cronin et al. 2003). In any situation where there may be interactions between surface waters and groundwater, stable O & H isotopes are a routine tool (e.g. Clark and Fritz 1997). The application of age indicators is necessary to ascertain rates of aquifer throughput and potential pollutant movement.

While hydrochemistry and stable isotopes are proven urban aquifer investigation techniques (e.g. Butler and Verhagen 1997), the use of age indicators is less routine. In the case of Bishkek, various constraints were apparent. Tritium (^3H), a valuable indicator in potentially polluted waters, was mainly ruled out because there was no local record of the precipitation input (though two groundwater check samples were collected—see below). While this could have been largely overcome by using the $^3H/^3He$ method, it was beyond the project budget. CFCs (chlorofluorocarbons), while simple to analyse are often compromised as dating agents in urban settings (e.g. Plummer and Busenberg 1999). SF_6 (sulphur hexafluoride), while much less compromised is present at significantly lower concentrations in groundwater and can therefore be measured less

Table 2 Properties of the main hydrogeologically important zones of Bishkek

	Setting	Unsat.zone (m)	Significance	Site no
A	Upper piedmont alluvial valley fill	10–1	Channel between Neogene loess foothills receiving both precipitation and major riverine recharge from R. Ala Archa. Site of main Bishkek wellfield (Orto Alysh; 90 public supply boreholes)	1, 3, 4
B	Unconfined piedmont fans	200–20	Zone of periurban coalescing coarse alluvial fans with deep unsaturated zone shallowing northwards into southern suburbs and city centre	5, 8, 9, 10, 11, 12, 17
C	River corridors	190–60	Unlined canalised river courses crossing Zones A and B; likely linear sources of recharge from influent reaches	2
D	Unconfined alluvial outwash plain	20–0	Urbanised zone with industrial, residential and commercial land use; relatively vulnerable due to shallow watertable and absence of low permeability surficial silty clay layer	14, 16, 18
E	Confined alluvial outwash plain	Artesian	As Zone D but much lower aquifer vulnerability due to artesian conditions, surficial silty clay layer and silt/clay bed interstratification.	6, 7, 13, 15

precisely (Busenberg and Plummer 2000). Ultimately it was decided to use CFCs and SF_6, in the expectation that even where rendered unusable as dating agents, their presence or absence might have tracer value in its own right, with ^3H samples from two deep sites to qualitatively assist interpretation.

The field study

The diversity of hydrogeological setting outlined above results in boreholes of widely different depths and screen settings. Thus, the main 90-borehole periurban Orto Alysh wellfield in the narrow Ala Archa alluvial valley fill of Zone A (Table 2; Fig. 4) typically has 150 m deep wells with

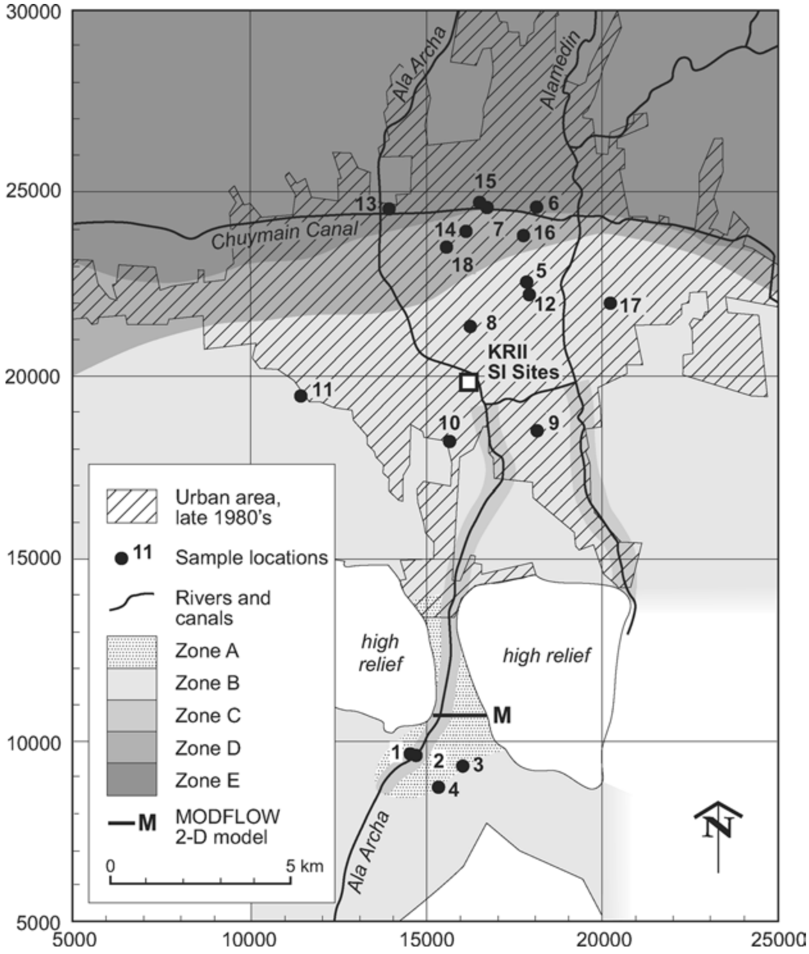

Fig. 4 Location of sampling sites and main hydrogeological zones of Bishkek

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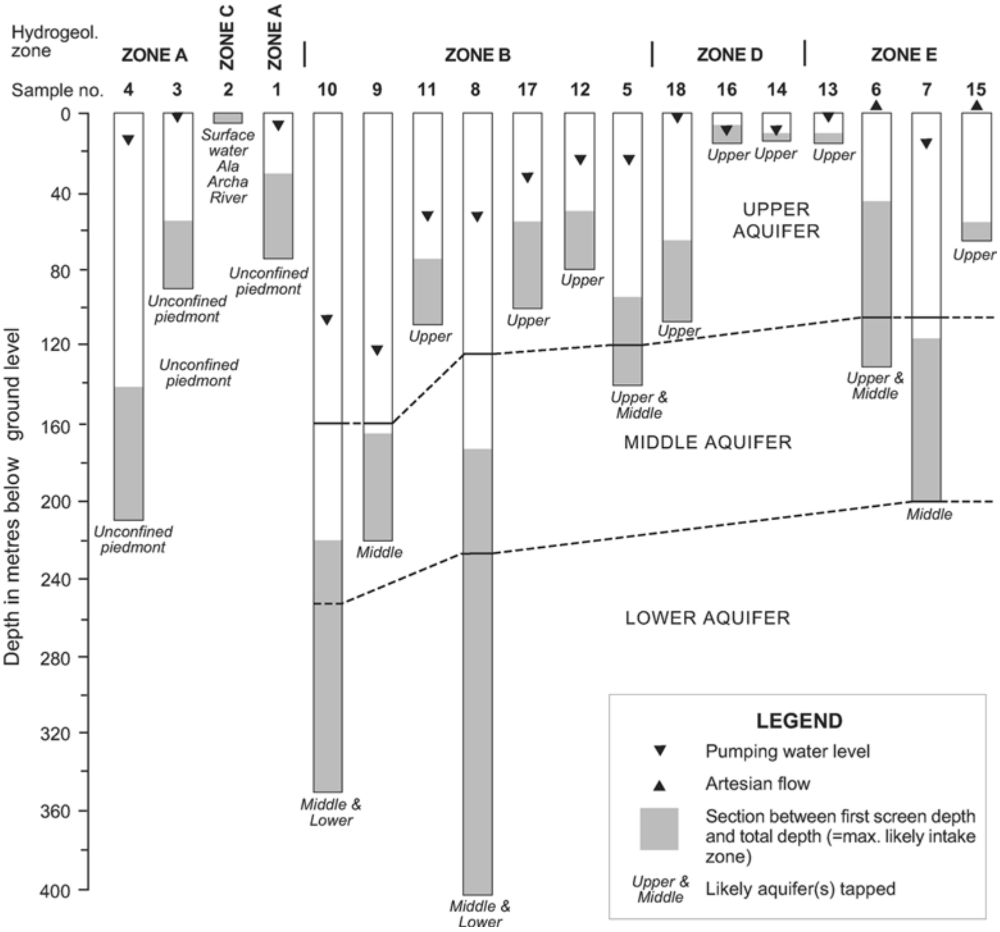

Fig. 5 Sampling borehole screen and depth distribution, Bishkek

about 40 m of screen set below 90 m, yet such wells 5 km down-gradient on the piedmont fans of the city's southern edge (Zone B) would hardly penetrate to the saturated zone, while those a further 8 km north on its northern edge encounter near-surface water levels or artesian conditions (Zone E). This diversity of abstraction setting is demonstrated in Fig. 5 where well screen intake zones and water levels are compared for the 18 sample sites. The results in this paper are interpreted in terms of the zoning and depth distribution information described in Table 2 and this figure.

Fieldwork comprised sampling and analysis of groundwater from urban and periurban boreholes, surface water and precipitation at sites selected to elucidate the likely role of induced leakage. Groundwater sites were chosen from inspection of existing borehole records in order to sample four of the five hydrogeologically distinctive zones in and around the city (Table 2; Fig. 4), and precipitation and river waters were sampled on the KSRII campus and also at the Orto Alysh wellfield.

While the highly diverse activities and land uses occurring on city catchments may produce a very wide range of potential contaminants in urban recharge, in practice groundwater impact studies for water management purposes often have to rely on a limited range of available data from major users like water utilities (Morris et al. 1994; Howard 2001). In this study the stable isotope and age indicator analyses were supplemented for comparison purposes with determinands typically sampled by an urban water utility; field physico-chemical measurements, major ion analyses, and a relatively small range of minor elements and organic indicators.

Sampling

Seventeen groundwater samples were collected over an eight-day period in early March 2002; 14 from producing wells under near-continuous pumping or free-flowing artesian conditions and 3 from shallow well sites with portable or existing domestic pumps (Fig. 4).

Early Spring flow in the suspected influent zone of the Ala Archa River where it traverses the main periurban wellfield was sampled at the same time. Daily sampling for O and H stable isotopes of precipitation and river/canal waters was conducted from March 2001 to February 2002 at KSRII. On-site parameters (temperature, pH, redox, dissolved oxygen and specific electrical conductivity) were monitored in flow cells until stable readings were obtained prior to sample collection. Samples for inorganic analysis were filtered through a 0.45 μm cellulose nitrate membrane and collected in two HDPE bottles, one aliquot being acidified to 1% with concentrated Aristar nitric acid. Stable isotope and

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volatile organic analysis samples were collected directly in glass vials, the latter with a PTFE -lined septum.

CFC and SF_6 samples were collected unfiltered without atmospheric contact in glass bottles contained within metal cans by the displacement method of Oster et al. (1996). This method ensures that the sample is protected from possible atmospheric contamination by a jacket of the same water. Samples for ^3H analysis were collected in 1 l glass bottles.

Analysis

Analyses were carried out at BGS Wallingford except where stated. Cations, phosphorus, silicon and sulphate were determined by inductively-coupled plasma optical emission spectroscopy (ICP-OES) on the acidified aliquots, and nitrogen species and chloride by automated colorimetry on the unacidified aliquots. Stable isotopes were analysed by mass spectrometry following standard preparation methods (CO_2 equilibration for $\delta^{18}O$, reduction with zinc shot for δ^2H, and acidification with phosphoric acid for $\delta^{13}C$–DIC). CFCs were determined by gas chromatography after pre-concentration by cryogenic methods. SF_6 was analysed similarly by Spurenstofflabor, Wachenheim, Germany. BTEX and MTBE were measured by gas chromatography by Alcontrol, Chester, UK and ^3H by electrolytic enrichment and liquid scintillation counting by RCD, Lockinge, UK.

Results

Field measurements; SEC, T, Eh, DO

The results of field measurements are given in Table 3. Higher specific electrical conductance (SEC) and temperature characterise shallow groundwater in the urban area (Figs. 6 and 7). The temperature anomaly below the city is significant; more than 3°C above the mean annual air temperature of 11.0°C, and detectable to more than 90 mbgl, as in sample sites 5 and 9. A geothermal or mechanical cause (from use of electrosubmersible pumps) can be discounted because the deeper wells, with uppermost screens set below 100 mbgl or more, show values similar to those in the rural intake zone A.

Table 3 Field physicochemical measurements

No	Zone	T (°C)	pH	Eh (mV)	DO (mg/L)	SEC (µS/cm)
2	C	7.2	8.12			268
4	A	11.6	7.11	370	7	1,306
3	A	11.0	7.34	370	9	883
1	A	10.8	7.68	426	10	598
10	B	12.4	7.85	378	7	685
8	B	12.5	7.83	227	6	668
9	B	14.7	7.52	371	7	975
11	B	13.5	7.31	392	8	1,252
17	B	13.2	7.28	306	4	653
12	B	18.5	7.36	366	4	1,095
5	B	16.7	7.33	323	6	1,100
18	D	11.0	7.36	348	4	655
16	D	18.0	6.75	332	4	1,555
14	D	13.9	6.78	421	2	1,080
6	E	18.3	7.20	386	4	1,190
7	E	12.6	7.72	235	6	750
13	E	13.0	7.60	367	-	770
15	E	12.8	7.42	464	5	620

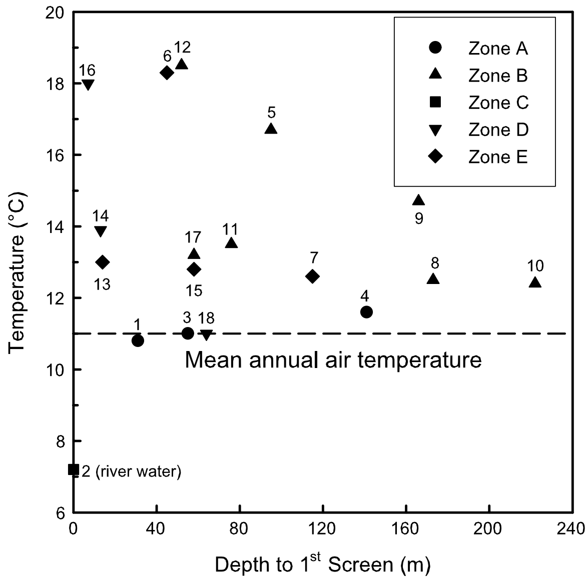


Fig. 6 Crossplot of sample temperature vs. depth to first screen

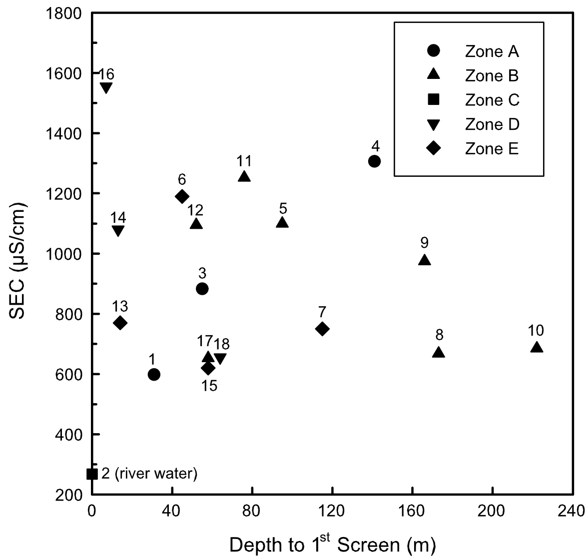
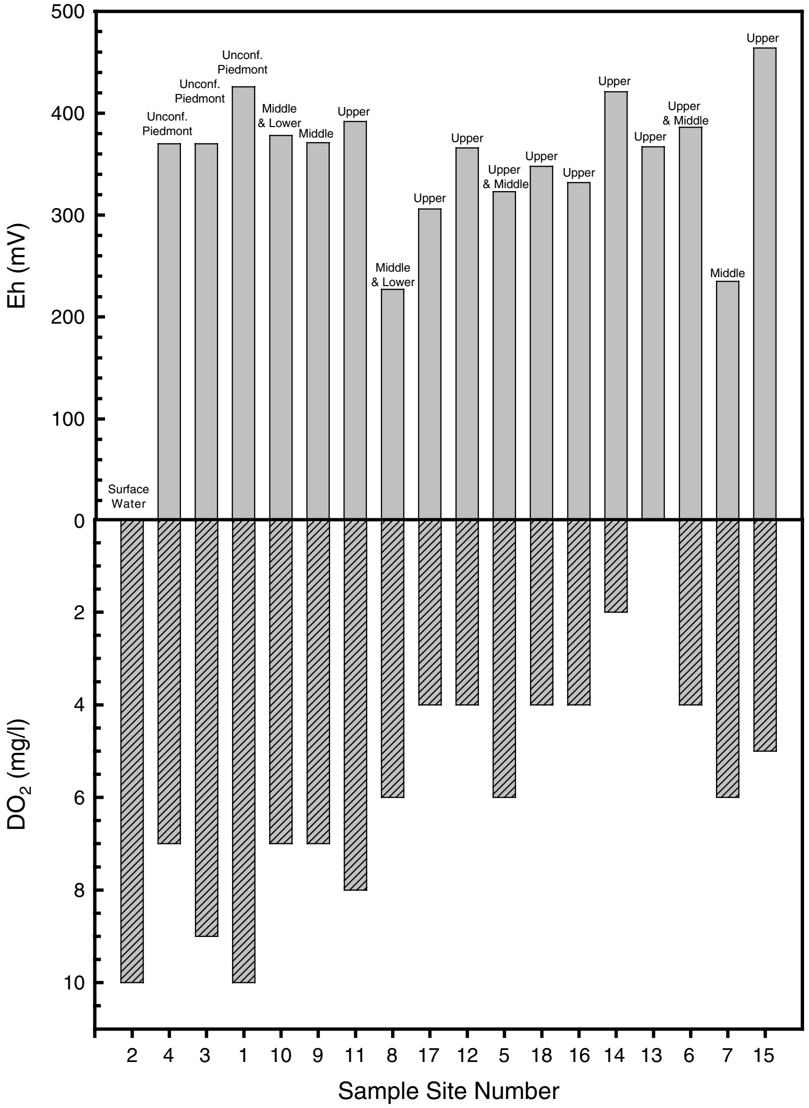


Fig. 7 Crossplot of SEC vs. depth to first screen

The moderately strong correlation between SEC and temperature (r^2=0.73) may point to wastewater, both from sewer leakage and from on-site sanitation, being a more important recharge source than leakage from the closed district hot water system, which is drawn from an eastern suburban wellfield represented by Site 7 (SEC of 750 µS/cm).

Redox (Eh) and dissolved oxygen (DO) measurements give a consistent pattern of aerobic conditions throughout

Fig. 8 Redox and dissolved oxygen measurements



the system, in all zones and from all depths sampled. While not necessarily indicating a short residence time, the presence of up to 6 mg/l dissolved oxygen from wells tapping the middle and lower aquifer (Fig. 8) at least means the aquifer matrix organic content must be low. It could also be inferred that despite the organic load infiltrating from wastewater and other contaminant sources, the groundwater circulation system must be active enough to cope with its oxidation demands.

In cities with more inhibited flow systems, this is not the case, and the oxidation of organic load produces progressively more reducing conditions. Depending on local circumstances (including the amount of petrogenic humic material disseminated through the matrix) a redox sequence of decreasing reaction energy-yield zones occurs, ranging from aerobic through nitrate-reducing, manganogenic, ferrogenic, sulphidogenic to methanogenic (Gooddy et al. 1997). In the geologically similar case of Santa Cruz, Bolivia, manganogenic to ferrogenic conditions were observed in several wells tapping shallow groundwater in the city centre, although compared to Bishkek anthropogenic and petrogenic sources of organic load were more prevalent and widespread in Santa Cruz (BGS and SAGUAPAC 1997).

Stable isotopes of O and H

Temporal distribution of precipitation and riverflow $\delta^{18}O$ and $\delta^{2}H$ is shown in Table 4 and Fig. 9.

Given that the Ala Archa River is partially fed by snowmelt, there is remarkably little change in isotopic composition, though the limited depletion around July may be due to snowmelt. Although the upper parts of the river's catchment include rugged 3,000 m peaks, the small isotopic range may indicate that much of the river's flow derives from precipitation on lower catchment slopes, located within a few km of Zone A. The reason for fluctuations at the beginning of the sampling period is unknown. Although spot sampling means that it is not possible to know

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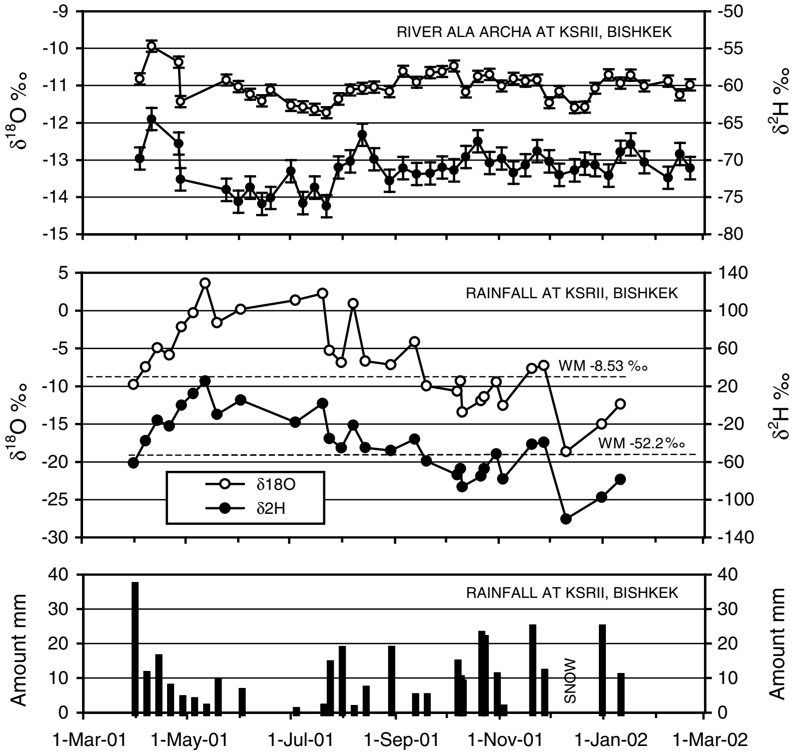
Table 4 River and precipitation (March 2001–February 2002) and groundwater (March 2002) stable isotope measurements, expressed in permil with respect to VSMOW

No	Source	Date	δ^{2}H	δ^{18}O	No	Source	Date	δ^{2}H	δ^{18}O	δ^{13}C
1R	SW	27:3–3:4	−10.82	−69.8		Pptn	11:4–17:4	−4.91	−16.1	–
2R	SW	4:4–10:4	−9.94	−64.5		Pptn	18:4–24:4	−5.84	−22.0	–
1R-V	SW	12:4–18:4	−10.48	−70.5	3P	Pptn	25:4–1:5	−2.14	−0.1	–
3R	SW	18:4–26:4	−10.37	−67.8	4P	Pptn	2:5–8:5	−0.28	12.3	–
2R-V	SW	19:4–26:4	−10.67	−69.3	5P	Pptn	9:5–15:5	3.62	25.3	–
4R	SW	27:4–3:5	−10.82	−69.5	6P	Pptn	16:5–22:5	−1.59	−9.8	–
3R-V	SW	4:5–10:5	−11.45	−74.5	7P	Pptn	30:5–5:6	0.18	5.3	–
4R	SW	11:5–17:5	−11.43	−72.6	8P	Pptn	04:07	1.38	−18.0	–
5R	SW	18:5–24:5	−10.85	−74.0	9P	Pptn	20:07	2.26	1.9	–
6R	SW	25:5–31:5	−11.03	−75.6	10P	Pptn	21:7–27:7	−5.26	−35.2	–
7R	SW	11:6–7:6	−11.23	−73.7	11P	Pptn	28:7–3:8	−6.84	−45.1	–
8R	SW	8:6–14:6	−11.41	−75.9	12P	Pptn	4:8–10:8	0.94	−21.1	–
9R	SW	15:6–19:6	−11.12	−75.1	13P	Pptn	11:8–17:8	−6.69	−45.0	–
10R	SW	25:6–29:6	−11.53	−71.5	14P	Pptn	26:08:00	−7.15	−48.1	–
11R	SW	2:7–6:7	−11.57	−75.8	15P	Pptn	12:09	−4.12	−36.0	–
12R	SW	9:7–13:7	−11.64	−73.7	16P	Pptn	19:09	−9.94	−59.0	–
13R	SW	14:7–20:7	−11.73	−76.2	17P	Pptn	4:10–5:10	−10.64	−73.7	–
14R	SW	21:7–27:7	−11.36	−71.0	18P	Pptn	09:10	−9.29	−67.2	–
15R	SW	28:7–3:8	−11.12	−70.2	19P	Pptn	10:10	−13.40	−86.4	–
16R	SW	4:8–10:8	−11.07	−66.6	20P	Pptn	18:10–21:10	−11.92	−75.1	–
17R	SW	16:8–17:8	−11.04	−69.9	21P	Pptn	23:10	−11.38	−67.2	–
18R	SW	20:8–28:8	−11.16	−72.8	22P	Pptn	27:10–28:10	−9.45	−51.5	–
19R	SW	29:8–5:9	−10.62	−71.1	23P	Pptn	2:11–3:11	−12.52	−78.1	–
20R	SW	6:9–13:9	−10.91	−71.9	24P	Pptn	20:11	−7.64	−41.3	–
21R	SW	17:9–21:9	−10.65	−71.8	25P	Pptn	26:11–27:11	−7.26	−39.3	–
22R	SW	24:9–28:9	−10.62	−71.0	26P	Pptn	7:12–9:12	−18.66	−120.5	–
23R	SW	1:10–5:10	−10.47	−71.4	27P	Pptn	31:12	−14.99	−97.4	–
24R	SW	8:10–12:10	−11.17	−69.6	28P	Pptn	11:01	−6.83	−78.6	–
25R	SW	15:10–19:10	−10.75	−67.5	29P	GW	4:03	−11.04	−74.9	–7.25
26R	SW	22:10–26:10	−10.70	−70.4	30P	GW	4:03	−11.46	−71.2	−14.38
27R	SW	29:10–2:11	−11.01	−69.8	2	GW	4:03	−11.63	−73.3	−14.47
28R	SW	5:11–9:11	−10.81	−71.7	4	GW	4:03	−11.51	−72.0	−12.82
29R	SW	12:11–16:11	−10.88	−70.7	3	GW	6:03	−11.56	−75.5	−11.12
30R	SW	19:11–23:11	−10.85	−68.8	1	GW	5:03	−11.47	−71.4	−13.33
31R	SW	26:11–30:11	−11.46	−70.2	10	GW	6:03	−11.71	−76.0	−13.60
32R	SW	3:12–6:12	−11.16	−72.0	8	GW	6:03	−11.50	−76.1	−10.49
33R	SW	11:12–15:12	−11.59	−71.4	9	GW	11:03	−11.59	−76.6	−14.74
34R	SW	18:12–21:12	−11.58	−70.5	11	GW	6:03	−11.80	−76.8	−11.93
35R	SW	24:12–26:12	−11.07	−70.7	17	GW	5:03	−11.34	−75.5	−13.38
36R	SW	2:1–4:1	−10.71	−72.1	12	GW	11:03	−11.53	−73.0	−13.86
37R	SW	8:1–11:1	−10.93	−68.9	5	GW	10:03	−11.62	−71.6	−12.98
38R	SW	14:1–17:1	−10.72	−67.9	18	GW	7:03	−11.34	−76.0	−12.17
39R	SW	20:1–25:1	−11.01	−70.3	16	GW	5:03	−11.77	−74.0	−15.14
40R	SW	5:2–8:2	−10.88	−72.4	14	GW	5:03	−11.76	−75.3	−11.66
41R	SW	11:2–15:2	−11.25	−69.2	6	GW	6:03	−11.54	−73.5	−14.72
42R	SW	18:2–21:2	−10.98	−71.1	7	GW	10:03	−11.61	−73.2	−9.62
1P	Pptn	28:3–3:4	−9.76	−61.1	13					
2P	Pptn	4:4–10:4	−7.43	−37.7	15					

SW: River Ala Archa at KSRII Bishkek. Pptn: Precipitation at KSRII Bishkek. GW: Groundwater at sites on Fig. 4

Fig. 9 $\delta^{18}O$ and $\delta^{2}H$ distribution in precipitation and river flow, Bishkek, March 2001–February 2002



exactly the bulk composition of the river, it seems likely to be approximately −11‰ $\delta^{18}O$ and −70‰ $\delta^{2}H$.

Precipitation at Bishkek varies in the usual way: isotopically enriched in summer and depleted in winter (especially when snowing). Comparison with the nearest (Kabul) station of the IAEA-WMO GNIP network (http://isohis.iaea.org) shows a similar range of compositions, allowing for the fact that GNIP sampling is monthly rather than weekly. In particular, both sites can show heavy isotope enrichment in the summer. The weighted means for Bishkek (−8.53‰ $\delta^{18}O$ and −52.2‰ $\delta^{2}H$) are also isotopically much heavier than the river flow and rule out the possibility of rainfall contributing significantly to the groundwater in the area (recharge is usually isotopically close to bulk rainfall—Clark and Fritz 1997). This conclusion is consistent with previous irrigation water balance and soil moisture studies for the Bishkek part of the Chuy Basin (Kaplinsky 1977). That study also analysed groundwater fluctuations, concluding that in an average year recharge could be as small as 2% of total rainfall (equivalent to <10 mm), mostly occurring in the spring. With a likely isotopic depletion in rainfall of −0.3‰ per 100 m rise ($\delta^{18}O$) or −2.5‰ ($\delta^{2}H$), there would need to be a rise of about 750 m in altitude for rainfall-derived recharge to figure prominently in the urban water balance.

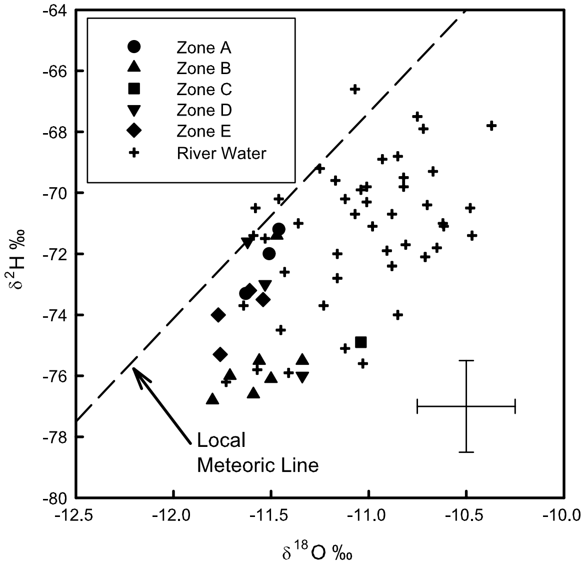


Fig. 10 $\delta^{18}O$ vs. $\delta^{2}H$ crossplot comparing Bishkek groundwaters with Ala Archa River flow at KSRII sampling point. Measurement error bar shown

Isotope data for groundwater sampled from the sites in Fig. 4 are reported in Table 4. Figure 10 shows the river waters plotted with the groundwater samples on a delta diagram. The groundwaters form a tight grouping (see measurement error bars), and overlap with the river waters, though at the depleted end of the range. It has already been shown that the rainfall weighted mean is much heavier (off-scale on Fig. 10). The overlap pattern may indicate that most leakage/recharge occurs at times of high flow when, presumably, depleted snowmelt is making a contribution. Such river-derived recharge can occur easily and ubiquitously in Bishkek because canalised offtakes permit amenity watering of roadside verges, parks and open spaces. Such snowmelt-fed irrigation is widely practised from April to October via an extensive but loosely controlled system of small open roadside irrigation channels.

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Table 5 CFC and SF$_6$ results for Bishkek groundwaters, in pmol/l or fmol/l as appropriate. Also shown are the data interpreted in terms of year of recharge (where possible), and alternatively as modern fraction (see text), both with estimated uncertainties

Site details				CFC-11			CFC-12			SF$_6$		
Site no	Zone	Likely aquifer (s) tapped	1st Screen depth	Conc. (pmol/l)	Bulk age yr. recharged	Mixed water mod. fraction	Conc. (mol/l)	Bulk age yr. recharged	Mixed water mod. fraction	Conc. (pmol/l)	Bulk age yr. recharged	Mixed water mod. fraction
2	C	Surface water	0	10.4	>Modern	2.0±0.4	6.08	>Modern	2.2±0.5	1.9	2000±2	0.86±0.1
4	A	Unconf. piedmont	141	46.4	>Modern	8.7±2	47.4	>Modern	17±3	4.1	>Modern	1.9±0.2
3	A	Unconf. piedmont	55	29.0	>Modern	5.5±1	20.9	>Modern	7.5±2	1.2	1993±2	0.55±0.1
1	A	Unconf. piedmont	31	10.0	>Modern	1.9±0.4	28.1	>Modern	10±2	1.7	1998±2	0.77±0.1
10	B	Middle and Lower	222	7.26	>Modern	1.4±0.3	2.15	1986±3	0.78±0.2	0.5	1983±3	0.23±0.1
9	B	Middle	166	28.2	>Modern	6.3±1.5	722	>Modern	305±60	0.3	1980±3	0.16±0.1
11	B	Upper	76	21.5	>Modern	4.8±1	57.6	>Modern	24±5	3.2	>Modern	1.7±0.2
17	B	Upper	58	301	>Modern	67±15	140	>Modern	59±12	1.0	1992±3	0.50±0.1
12	B	Upper	52	58.2	>Modern	13±3	318	>Modern	135±27	1.9	2002±2	1.0±0.1
5	B	Upper and Middle	95	62.5	>Modern	14±3	137	>Modern	58±12	1.3	1995±2	0.68±0.1
18	D	Upper	64	84.1	>Modern	16±3	1386	>Modern	500±100	2.6	>Modern	1.2±0.1
16	D	Upper	7	273	>Modern	61±12	39.2	>Modern	17±3	1.7	2000±2	0.89±0.1
14	D	Upper	13	30.9	>Modern	6.9±1.5	193	>Modern	82±15	6.7	>Modern	3.5±0.1
6	E	Upper and Middle	45	36.4	>Modern	8.1±1.5	235	>Modern	99±20	1.7	2000±2	0.89±0.1
7	E	Middle	115	32.6	>Modern	6.1±1.5	429	>Modern	155±30	1.1	1992±3	0.50±0.1
15	E	Upper	58	33.0	>Modern	6.2±1.5	4625	>Modern	1670±330	2.0	2001±2	0.91±0.1

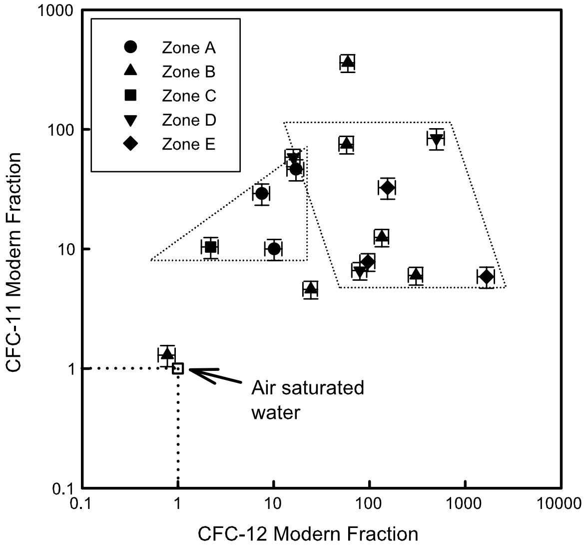

Fig. 11 Crossplot showing the almost universal enrichment of CFC-11 and CFC-12 in Bishkek groundwaters. Atmospherically-saturated water is assigned a modern value of 1 for both CFCs

CFCs and SF$_6$

CFC-11 and CFC-12 were found in all samples (Table 5), even from deep boreholes with uppermost screens at 115–222 m depth. As well as reporting CFC and SF$_6$ measurements, Table 5 includes interpretations of the data in two forms. The first of these is a bulk age expressed as year of recharge based on simple intergranular 'piston' flow and dissolved concentrations calculated from atmospheric input curves (Busenberg and Plummer 2000), while the second assumes the measured concentration is the product of mixing between modern recharge and >50 year-old 'dead' water, and reports it as 'modern fraction'. Thus a water may have modern fraction values of between 0 (over 50 years old) and 1 (modern), or >1 (contaminated). In the last case it is clearly impossible to assign a piston flow age for that particular species. It should be noted that CFC and SF$_6$ solubilities vary with recharge temperature; the calculated values in Table 6 are based on a recharge temperature of 11°C for Sites 1, 2, 3, 4, 7, 10, 15 and 18 (derived from annual average air temperature) and 14.5°C for Sites 5, 6, 9, 11, 12, 14, 16 and 17 (urban recharge temperature).

An almost universal element of enrichment relative to a modern atmospheric input was encountered in all wells except the deepest, most upgradient Zone B borehole at Site 10. The Ala Archa River and all of the wells in the Orto Alysh wellfield (which draw directly or indirectly from what is regarded as a near–pristine rural catchment) were all affected, and one deep borehole with uppermost screen at 166 m depth (Site 9) was enriched in CFC-12 by more than two orders of magnitude over modern atmospheric input.

In the upgradient Orto Alysh wellfield (sites 1, 3, 4) CFC-11 is relatively more enriched than CFC-12, but the reverse is the case in the city area. As CFC-11 is more than three times as soluble as CFC-12 the reasons for this pattern

Table 6 Major and selected minor inorganic species for Bishkek groundwaters

No	Zone	Ca	Mg	Na	K	Cl	SO_4	HCO_3	NO_3–N	SiO_2	Ba	Sr	Fe	Zn
		(mg/l)									(µg/l)			
2	C	24.3	2.5	5.40	0.7	1.10	19.4	71.0	1.2	7.14	20	131	26	6
4	A	99.6	17.7	32.5	2.0	13.8	53.6	321	6.6	17.15	127	767	36	15
3	A	72.8	7.24	19.0	1.7	12.5	38.4	213	3.1	11.76	59	613	27	15
1	A	54.2	4.51	5.80	1.1	4.80	19.7	150	3.1	10.84	48	245	28	12
10	B	53.9	5.65	15.0	1.4	6.40	32.8	162	3.3	12.13	52	347	52	11
8	B	51.2	5.56	13.2	1.3	7.30	32.2	152	3.2	12.58	46	341	53	10
9	B	78.9	7.05	17.4	2.5	11.5	37.1	218	6.4	12.62	129	450	46	12
11	B	101	12.8	26.4	2.8	11.2	46.9	279	12.7	17.22	163	672	60	14
17	B	94.3	9.58	30.3	3.0	25.9	41.0	267	8.3	16.09	123	664	46	13
12	B	89.6	7.67	22.2	3.2	14.0	44.8	235	8.3	15.29	152	471	70	16
5	B	88.2	8.11	21.0	3.3	14.3	46.1	244	8.0	13.90	143	510	85	13
18	D	95.5	9.64	28.4	2.5	18.9	55.8	256	10.8	15.08	157	646	59	14
16	D	215	21.9	101	4.8	93.6	169	344	66.8	18.76	45	618	63	17
14	D	164	18.7	50.8	3.5	51.8	158	314	27.1	19.40	47	572	38	18
6	E	95.2	8.78	30.2	2.9	15.0	52.7	253	7.9	16.71	158	608	32	13
7	E	55.3	6.62	15.0	1.6	11.4	34.8	162	4.2	13.92	70	420	52	12
13	E	112	11.2	34.0	2.4	36.6	65.3	246	16.0	14.52	286	684	30	14
15	E	91.1	9.65	26.1	2.2	14.5	54.8	238	8.3	14.69	155	635	33	13

are unclear but may be due to the relative availability in different sources of contamination.

The universal presence of CFCs, not only in the coarse unconfined piedmont fans but also further north throughout the more interstratified outwash plain deposits, suggests deep penetration of recharge. The contamination in this recharge could originate either from river/canal leakage or from local urban/industrial sources within the city. Its presence in wells of all types appears to rule out site-specific leakage of contaminated surface water down casing annuli. Moreover, while the very presence of CFCs in the middle and lower aquifer is striking, the additional evidence of widespread enrichment suggests that the intensive pumping regimes that characterise public supply abstraction must be driving deep flow systems, with urban recharge penetrating at rates of at least 5 m/year.

Previous studies (MacDonald et al. 2003; Darling et al. 2004) indicate that SF_6 is much less affected by sources of contamination like landfills/informal disposal that may profoundly modify CFC concentrations and this seems to be also the case in Bishkek. SF_6 was detected in all 16 samples taken, but only four of the samples showed ‘above modern’ concentrations indicating a local source of low-level enrichment affecting the groundwater (Fig. 12).

From Table 5, the question arises as to which interpretation (mixing or piston flow) is the most appropriate. The O and H stable isotope data referred to earlier suggest that fluvial recharge, either direct or via canal bed leakage, is a predominant component and as the aquifer system is intergranular, this in turn suggests that the samples may be most meaningfully interpreted as bulk ages assuming piston flow.

In this case, the SF_6 ages for the 12 samples least affected by local contamination range from modern to about 20–25 years. The CFC-12 and SF_6 bulk ages of Site 10, a deep Zone B borehole apparently unaffected by local contamination of either indicator, show good agreement at 1986±3 years and 1983±3 years respectively. There is a moderate correlation with intake screen depth (r^2=0.75, Fig. 13) and the fitted linear regression curve suggests vertical transit rates of about 8–9 m/year.

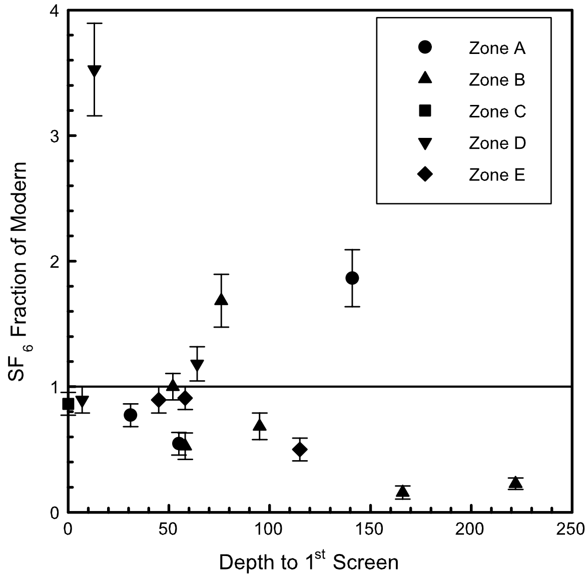

Fig. 12 Crossplot of SF_6 converted to modern fraction vs. first screen depth

The CFC and SF_6 data have not been adjusted to account for the excess air that is normally entrained during infiltration of recharge. Its presence, which is of most significance to SF_6 because of its low solubility, would give ages that are too young by perhaps 5 years for an excess of 15%, a typical value for sandstone (Wilson and McNeill 1997).

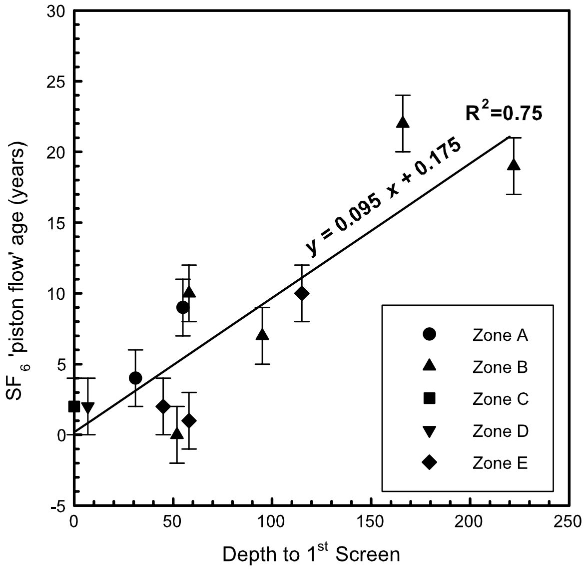

Fig. 13 Crossplot of SF_6 expressed as bulk age vs. first screen depth

The value for recharge of partly riverine origin is however speculative.

If a mixing interpretation is preferred, the degree of mixing between "established" groundwater and modern recharge from river and canal sources can to some extent be assessed by comparison with silica (Fig. 14), chosen because it should be relatively unaffected by differing chemical inputs from pollutant sources. Surface water (site 2) is least 'evolved' in terms of silica concentration and has a modern SF_6 signature. Deep groundwater appears to be around 12 mg/l SiO_2 with an apparent residence time of around 20 years, though alternatively could be >50 years mixed with about 15% of recent water. The latter is the more hydrogeologically reasonable for Sample sites 9 and 10, given the extremely thick unsaturated zone in the southern upgradient area of Zone B. Beyond a value of 12 mg/l, the rise in SiO_2 probably results less from residence than from mixing with relatively unbuffered waters made acidic by the oxidation of organic pollutants, as reflected in the high HCO_3 concentrations and lower pH in the shallowest boreholes (see sites 14 and 16 in Tables 3 and 6). One implication of this observation is that in the northernmost Zone E, where artesian heads exist under non-pumping conditions, flow systems may be rather shallower than those further south, and possibly influenced by mixing with leakage from the major Chuy Main irrigation canal which is nearby.

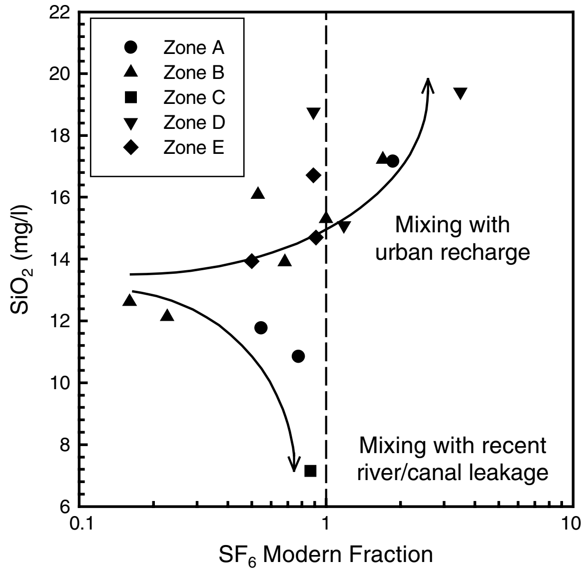

Fig. 14 Crossplot of SF_6 expressed as modern fraction vs. silica, showing two apparent mixing trends

Tritium

Two deep borehole sites in Zone B were analysed for ^3H. Sites 9 and 10 (uppermost screen depths of 166 m and 222 m) showed values in tritium units of 32±2 TU and 48±3 TU respectively. While the lack of a ^3H precipitation record in Kyrgyzstan and neighbouring states permits only a qualitative interpretation, this again supports deep penetration of recent recharge. The presence of ^3H in a groundwater indicates at least a proportion of water recharged within the last 40–50 years but the activity levels seem high for an input derived only from the thermonuclear testing peaks in the early 1960s. An additional, more local source of contamination is indicated, as with the CFC and SF_6 results.

Major elements

Results for major species are given in Table 6. A general pattern of baseline concentrations in Zone A and in the middle and lower aquifers of Zones B–E is supported by the distribution of the common major ion urban wastewater indicators of Cl^-, NO_3^- and SO_4^{2-} (Fig. 15). Two- to eightfold increases in these anion concentrations occur in wells with screens open above about 65 m. The nitrate enhancement in several of these urban-location shallower-screened boreholes is quite marked. However, evidence from these indicators is weak for deeper penetration of recent recharge.

There is a good correlation between chloride and total inorganic nitrogen (TIN) ($NH_4^+ + NO_2^{2-} + NO_3^-$, $r^2 = 0.92$, Fig. 16). Concentrations are highest both northwards into the urban area and in boreholes with intakes above 60 m depth. TIN is present almost entirely as nitrate in these samples ($NH_4^+ + NO_2^{2-}$ values are all ≤ 0.02 mg/l-N) and the chloride to nitrogen ratio is approximately 1:1.6. This is almost four times the average molar ratio of 1:5 in excreta, sometimes used as a guide to the extent of domestic wastewater contribution to recharge. The proportion of organic nitrogen load converted by nitrification into nitrate is likely to be high given the aerobic conditions, so the relatively high chloride:nitrogen ration implies that other sources of chloride are present. The most likely candidate is salt leached from localised winter road de-icing.

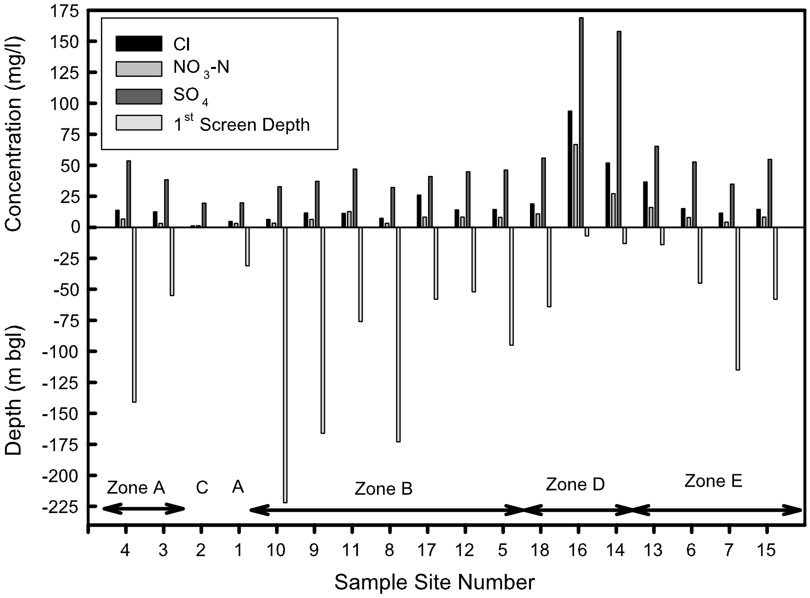

Fig. 15 Major anionic urban recharge indicators

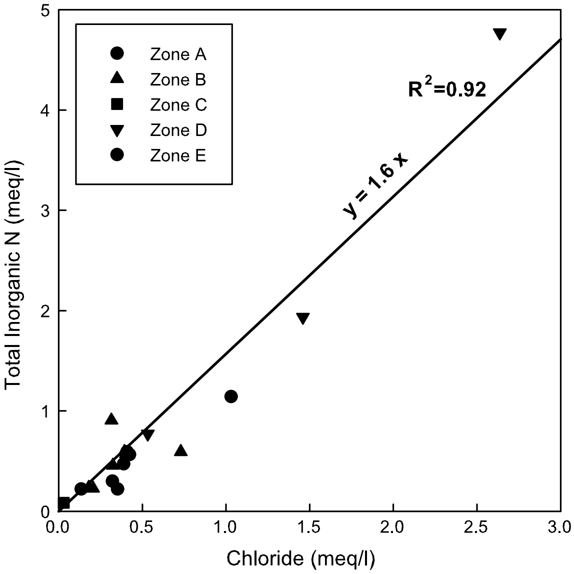

Fig. 16 Crossplot of chloride vs. total inorganic nitrogen (TIN)

As a contaminant source, road de-icing salts appear to be minor so far, despite harsh continental winter conditions.

Minor elements and hydrocarbon indicator compounds

The range of minor elements was limited to those determined by standard ICP-OES techniques (see Table 6) and most were not markedly increased over the baseline values observed in Zone A rural wells and river baseflow, except in the city centre above 90 m depth. Passive markers like B, Ba, Cu, Zn, Fe, Mn, Zn, Ba, K, that have proved useful elsewhere in cities with an industrial history, here provided little evidence of significant penetration of contaminated recharge (Fig. 17). Elements not shown but below detection limit include P (<100 μg/l); B (<100 μg/l); Cu (<8 μg/l) Ni (<5 μg/l); Mn (<2 μg/l); Cd (<1 μg/l); and Al (<0.01 μg/l). Bishkek during the Soviet era had a manufacturing base which included metal-processing, mechanical engineering and textiles. This period of perhaps 45–50 years of strong manufacturing activity from the early 1940s onward has since declined, but in a city largely underlain by unconfined aquifer, the absence of such indicators is striking. Factors present that would inhibit metal dissolution in recharge include an aerobic environment (measured dissolved oxygen and redox of >2 mg/l and >225 mV respectively) and well-buffered pH conditions (6.7–7.9), both persisting to significant depths.

The range of analysed hydrocarbon compounds was limited to those most generally associated with manufacturing industry and fuel-filling stations (BTEX and MTBE). All sample results were below the detection limits of 10 μg/l for each of the five analysed hydrocarbon compounds. One possible reason is that the unsaturated zone in the south and centre of the city is >30 m thick, providing ample opportunity for volatilization.

Testing urban leakage interpretation feasibility by water balance calculations and MODFLOW model

Chemical evidence suggests short residence times and mixing of groundwater and river leakage for groundwater abstracted from the Ala Archa wellfield. To verify the hydraulics of this situation, various numerical approaches were adopted. A water balance for the wellfield was undertaken, travel times calculated by the Darcy equation were approximated and a simple two-dimensional vertical slice MODFLOW model was built.

Simple water balance calculations support the chemical evidence that short groundwater residence times are likely and that mixing of groundwater and river leakage occurs, induced by intense pumping in the Ortho Alysh wellfield.

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Fig. 17 Minor element urban recharge marker species

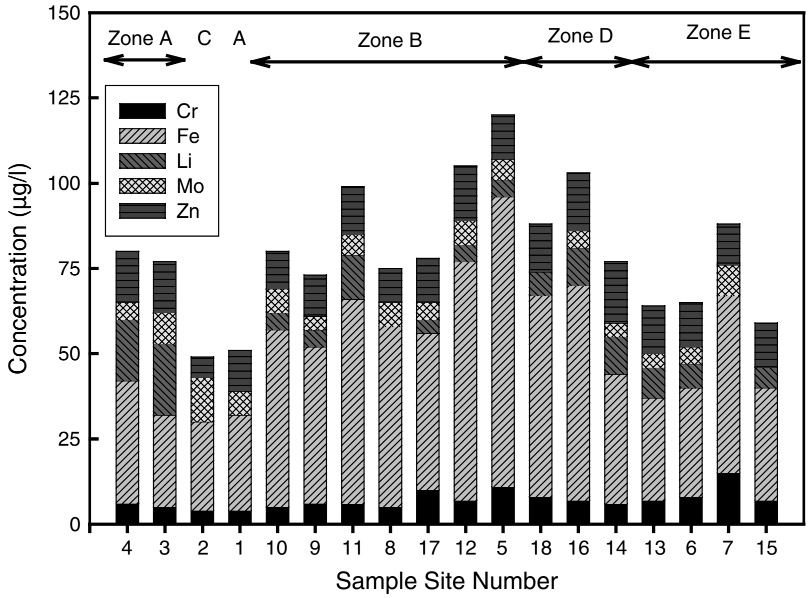
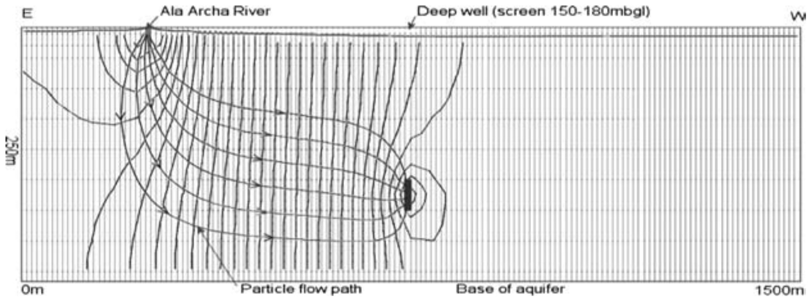


Fig. 18 East-west cross-section through the groundwater flow field in the Ala Archa valley at Orto Alysh as simulated in MODFLOW (see also M in Fig. 4)



On the basis of available groundwater level information for the area, the hydraulic gradient in the Ala Archa valley was approximated. The cross sectional area through which flow can occur is well defined by the extent of the valley fill. Calculations from field values based on a 1,500 m × 250 m saturated aquifer cross-section, a hydraulic conductivity of 12 m/d and a hydraulic gradient of 0.028 suggest a flow rate of about 1.5 m^3/s into the Ala Archa valley. The amount abstracted from the Ortho Alysh well field however is 3.5 m^3/s, resulting in an apparent water balance deficit of about 2 m^3/s. Under steady-state conditions, this deficit is supplied by induced river leakage and natural recharge, but the limited rainfall and aerial extent of the Ala Archa valley means that the latter can only account for a comparatively small proportion of the deficit. Thus extensive mixing of groundwater and induced leakage from the river is likely, supporting the suggestion from the O and H isotope data that river leakage could predominate over local rainfall as a primary source of aquifer recharge upstream of the city. It also suggests that groundwater flow velocities are likely to be high within the valley. Assuming an effective porosity of 0.2 for the valley fill, an average linear velocity of groundwater of 1.68 m/d (over 600 m/year) is indicated.

Whether pumping-induced leakage from the river could penetrate as deeply and quickly in the Orto Alysh wellfield as the CFC and SF_6 results suggest was tested by simple steady-state groundwater flow modelling, undertaken using the numerical code MODFLOW (McDonald and Harbaugh 1988). Thereby a simplistic approach was taken, using a vertical slice model through the Ala Archa valley from E to W to simulate the vertical distribution of horizontal flow to a well. The approach allows for fastest possible travel times to be established between the river and wells at different locations and depths under varying hydrogeological conditions. The model does not take radial flow to the well into account, neglecting throughflow and local non-river recharge, thus recharge solely from induced bed leakage is simulated and represents the shortest travel-time cases. Any mixing of river leakage with groundwater throughflow (which is the likely case), results in higher bulk groundwater ages within the wellfield, depending on the age of those waters and the degree of mixing, which is consistent with the age indicator results.

Several steady-state model runs were undertaken to test the effect on travel times from the river source to the well for varying hydrogeological parameter values and pumping rates within ranges likely to be encountered in the vicinity of the Orto Alysh wellfield. The parameter values used in six representative scenarios are shown in Table 7. The model results support the deduction from the water balance calculations referred to above, that bed leak-

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Table 7 Parameter values of MODFLOW two-dimensional cross-section model through Ala Archa valley with resultant travel time results

	Borehole screened depth (m)	Hydraulic conductivity (m/d)		Porosity	Well pumping rate (m^3/d)	Min, max. travel time (years)	Average travel time (years)
		Horizontal	Vertical				
Base case 1 (shallow well)	30–60	12	12	0.2	3,650	0.97–2.17	1.4
Base Case 2 (deep well)	150–180	12	12	0.2	3,250	1.88–3.4	2.31
Scenario 1 (deep well)	150–180	12	6	0.2	3,250	1.81–4.0	2.43
Scenario 2 (deep well)	150–180	12	3	0.2	3,250	1.76–4.66	2.57
Scenario 3 (deep well)	150–180	12	12	0.3	3,250	2.83–5.1	3.47
Scenario 4 (deep well)	150–180	12	12	0.1	3,250	0.94–1.7	1.16
Scenario 5 (deep well)	150–180	12	12	0.2	3,750	1.63–2.93	2.0
Scenario 6 (deep well)	150–180	12	12	0.2	2,750	2.24–4.04	2.75

age induced from the Ala Archa River under the continuous pumping regime practised in this highly permeable aquifer, could arrive rapidly at continuously pumped wells. Shallow as well as deep boreholes arrival times were on average less than 4 years for all the combinations simulated, even that with a K_h/K_v ratio of 4, representing coarse clastic anisotropy. Higher porosities, lower pumping rate and increased anisotropy prolong the travel time. The simulated arrival times translate into groundwater velocities ranging from 0.4 m/d to 1.9 m/d between river and well.

The results from the various numerical approaches support the geochemical interpretation that rapid and deep penetration of pumping-induced river recharge is possible in the unconfined piedmont zones. Additional field studies would be necessary to verify the extent to which riverflow is able to supply the large water quantities implied by the numerical model and the water balance calculation.

Further north in the city itself, there is also ready and widespread availability of surface water recharge from river/irrigation canals and amenity watering, but the flow system is too complex to be amenable to simple scenario modelling.

Discussion

Significance of results in understanding urban water budget

Taken together, the results suggest that pumping from the city's network of boreholes has created deep and dynamic flow patterns in the Bishkek aquifer system, with laterally and vertically dispersed groundwater samples showing evidence of waters less than 25 years old in periurban and urban areas alike and at depths exceeding 200 m. Considering the semi-arid setting of Bishkek, and the presence in places of an extremely deep water table, the widespread extent to which recent recharge has penetrated is remarkable, with implied vertical infiltration rates of several metres per year and more.

South of the city, the key elements driving such deep flow patterns on the demand side seem to be pumped withdrawals from deep boreholes, and on the supply side river/canal leakage. This can be readily appreciated in the southern half of the city (Zones A–C), where coarse clastics comprise the unconfined piedmont and associated alluvial fills of the narrow Ala Archa and Ala Meddin valleys exiting through the Alatau foothills. Their coarse nature permits the ready establishment of vertical flow in the Orto-Alysh wellfield whose boreholes have deep screen intervals (typically 90 m to 150 mbgl). Modelling has shown how pumping-induced bed leakage of the Ala Archa River helps maintain the productivity of this wellfield. On emergence from the foothills, the Ala Archa, Ala Meddin, VB Chuy main canal and various subsidiary channels must lose more water south of the city centre traversing the piedmont fans whose topography produces a deep regional water table shallowing northwards.

It is in this zone that the age indicator findings are most remarkable because here, in a zone of generally very deep water table, the borehole screen settings exceed 150 mbgl. The vertical infiltration rates of 5–12 m/year implied by the results can be reconciled if the critical but very narrow leakage zones beneath the river and main canal channels are almost permanently saturated. The possibility of by-pass flow down casing annuli, either of the sampling well or via nearby abandoned boreholes, can never be entirely excluded, but is considered very unlikely to account for the age indicator results in this study. Not only are the sampling boreholes of various ages, designs and drilling construction methods, but also all of the public supply wells that were sampled were housed in solidly constructed pumping stations or concrete-floored roofed chambers where the scope for extensive leakage of surface runoff would be very limited.

Sources of potential recharge further downgradient within the city are numerous (Fig. 2), as the rivers and main canals feed out to the widespread street-side network of minor channels which water amenity areas within the city. The only controls on water entry along all these channels are the bed permeability (likely to be high because channels are mainly unlined with moderately steep gradients preventing siltation) and flow duration (9+ months/year). Isotopically, the groundwater below the city is similar to these surface waters but there are also other, quite distinct, sources of urban recharge. These include leakage from the pipe infrastructure (mains potable, hot water, district heating, sewers) and percolation from on-site sanitation. Although as yet unquantified, their presence as a component of recharge is detectable by the indicators of chloride, nitrate, sulphate and some minor element species variously to about 65–90 m and by temperature anomaly to more than 100 m depth. Effective as these simple parameters were in indicating the presence of urban recharge, the true depth of active flow systems was only identified by the CFC and SF_6 tracers, evidenced both by their universal presence and by the extent of local CFC enrichment.

Constraints on interpretation from CFC enrichment in urban/industrial areas

It is as well, however, to recall the very small volumes of CFCs that would be required to bring this localised contamination about. Modern recharge derived from atmospheric circulation contains only 5.5 pg/l CFC-11 (5.5×10^{-12} g) and 3.0 pg/l CFC-12 (3×10^{-12} g). The combined volume of CFC-11 and CFC-12 required to contaminate a 150 m thickness of aquifer with a 20% porosity over an area of 1 km^2 to a level equal to modern CFCs in rainfall is less than 0.2 ml:

$$1000\,\text{m} \times 1000\,\text{m} \times 150\,\text{m} \times 0.2$$
$$= 3 \times 10^{7}\,\text{m}^{3} = 3 \times 10^{10}\,\text{litres}$$

$$\text{Amount of CFC} - 11\ \text{required}$$
$$= (3 \times 10^{10})(5.5 \times 10^{-12})$$
$$= 0.165\,\text{g} \equiv 0.111\,\text{ml}$$

$$\text{Amount of CFC} - 12\ \text{required}$$
$$= (3 \times 10^{10})(3 \times 10^{-12})$$
$$= 0.09\,\text{g} \equiv 0.069\,\text{ml} \qquad \text{Total: } 0.18\,\text{ml}$$

To contaminate a 100 km^2 block to 10 times the modern signature would need less than 70 ml of CFC-12; a single standard domestic refrigerator may contain 600–1,000 ml of CFC-12. It is for this reason that groundwater samples from residential and industrial sites often contain concentrations of chlorofluorocarbons above modern atmospheric levels, in some instances by several orders of magnitude (Thompson and Hayes 1979; Busenberg and Plummer 1992). Elevated atmospheric concentrations may occur close to industrial centres (Lovelock 1972; Cook et al. 1996). Although CFC-11 and CFC-12 are both dense non-aqueous phase liquids, CFC-11 is a liquid at a groundwater temperature of 10°C whereas CFC-12 is a vapour (Table 8). Uses are various but CFC-12 has been mainly employed as a refrigerant.

Bishkek aquifer protection issues

Prior to the hydrochemical results described here, well drill-logs were the sole quantitative means in Bishkek to deduce the likely threat to deep public supply boreholes from penetration of potentially-contaminated urban recharge. As these indicate frequent and relatively thick silty horizons in Zones D and E, it would have been reasonable to assume only very limited leakage of recharge below the ‘upper’ aquifer and minimal threat to wells with deeper screen settings. This is plainly not the case; the environmental tracer results do not support a tripartite division of the alluvial aquifer beneath Bishkek but instead suggest that conceptually a single low-anisotropy patchy aquifer is a more realistic approximation of the flow system, at least for the uppermost 250 m.

Table 8 Properties of CFC-11 and CFC-12 (from Plummer and Busenberg 1999)

Property	CFC-11 ($CClF_3$)	(CFC-12 CCl_2F_2)
Boiling point (°C)	23.8	−29.8
Vapour pressure at 25°C (psi)	15.3	94.5
Liquid density at 25°C	1.48	1.31
Solubility at 25°C (mol/l/atm) (Warner and Weiss 1985)	.0103	.0029

Awareness of such high rates of movement and the widespread extent of vertical leakage would have influenced the outcome of the groundwater vulnerability mapping of the city undertaken as a separate exercise prior to this study (ÓDochartaigh et al. 2000). Data availability, considered moderate to good in comparison with other developing cities (Morris et al. 2001) dictated the selection and weighting of four intrinsic vulnerability criteria; geological type, depth to groundwater, surface hydraulic conditions and presence or absence of a surficial low permeability layer. As with all overlay-and-index methods, there is an element of subjectivity in the assignation of weights to the components of a vulnerability index, and with hindsight the depth to groundwater criterion would have been given less weight in the score. The effect would have been to increase the relative vulnerability of the piedmont area south of the city, a conclusion with obvious development planning implications.

Similarly, there are major implications for the city’s future water management, because it means that despite its intergranular nature and great thickness, the Bishkek aquifer system is, in contaminant vulnerability terms, a rapid response system. The absence of extensive low-permeability horizons that would protect underlying aquifers is implicit in these findings. Fortunately, so far, the urban aquifer seems to have escaped major water quality deterioration, partly because the quantity and quality of surface water recharge has been high and partly because contaminant loadings appear to have been relatively light. Were either circumstance to change, if for instance the Ala Archa catchment became urbanised or winter road de-icing were introduced, the impact on potable water quality would start to be felt after only a very few years, even in deep boreholes.

The implication is that water resource protection for the Orto Alysh wellfield needs to extend upstream to include the whole of the Ala Archa catchment, not just the immediate environs of the wellfield. In this more extensive zone,

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part of which fortuitously is a national park, strict and enforced development controls are required to constrain contaminant loadings, with the aim of achieving pristine catchment status. This is a perfectly feasible objective at the city's present development stage because there is ample scope for expansion of the city towards the east, west and north of the current urbanised area. Maintenance of high water quality standards in the Ala Archa and Ala Meddin rivers (and their canal offtakes) south of the Chuy Main Canal is also vital, given the key role of these upper reaches in recharge.

Summary and conclusions

Environmental tracers (stable isotopes, age indicators and other hydrochemistry) have been used to assess the extent and rate of penetration of recent recharge to the aquifer system beneath the groundwater-dependent city of Bishkek, Kyrgyzstan. Stable O and H isotope results confirm that bed leakage from rivers and canals draining from the Alatau mountain range predominate over local rainfall/snowfall as a source of aquifer recharge. Extensive urban and periurban pumping for city use has induced deep infiltration of recharge into the aquifer system. While standard hydrochemical indicators have identified the influence of urban recharge to depths of 25–100 m, CFC, SF_6 and ^3H measurements demonstrate that induced leakage has established much deeper flow systems.

Almost universal enrichment of CFC-11 and CFC-12 in urban and periurban sources prevented direct use of CFCs as an age indicator, although their mere presence shows that recharge less than 50 years old has infiltrated. SF_6 appears to be much less affected by local pollution sources. This tracer permitted a refinement in residence time estimates and indicated bulk recharge ages of 20–25 years or less from all sites sampled, a finding compatible with a MODFLOW two-dimensional model set up for the periurban wellfield to test the interpretation of rapid and extensive infiltration inferred from the hydrochemical results.

In groundwater protection terms, three points emerge from this study. Firstly, induced leakage can completely transform the groundwater flow system beneath a city and any strategy for sustainable use of deep urban aquifers for water supply needs to take this into account. Secondly, vulnerability assessments must be informed by field monitoring to substantiate and calibrate a qualitative procedure that necessarily contains subjective elements. Thirdly, environmental tracer studies of this type have great potential to improve the understanding of urban aquifer systems, to the benefit of city water infrastructure management.

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