Drinking water quality in Nepal's Kathmandu Valley: a survey and assessment of selected controlling site characteristics

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Abstract Water was sampled from over 100 sources in Nepal's Kathmandu Valley, including municipal taps, dug wells, shallow-aquifer tube wells, deep-aquifer tube wells, and *dhunge dharas* (or stone spouts, public water sources that capture groundwater or surface water). Information was gathered on user preference and site and well characteristics, and water was examined for indicators of contamination from sewage, agriculture, or industry. Most problematic were total coliform and *Escherichia coli* bacteria, which were present in 94 and 72% of all the water samples, respectively. Contamination by nitrate, ammonia and heavy metals was more limited; nitrate and ammonia exceeded Nepali guidelines in 11 and 45% of the samples, respectively. Arsenic and mercury exceeded WHO guidelines in 7 and 10% of the samples, respectively, but arsenic never exceeded the less strict Nepali guideline. Significant differences existed in contamination levels between types of sources; dug wells and dhunge dharas, being the shallowest, were the most contaminated by bacteria and nitrate; deep-aquifer tube wells were the most contaminated by arsenic. Whereas *E. coli* concentrations decreased with depth, iron and ammonia concentrations increased with depth. These relationships account for people choosing to drink water with higher levels of bacterial contamination based on its superior (non- metallic) taste and appearance.

Résumé Plus de 100 points d'eau de la Vallée de Kathmandu au Népal ont été échantillonnés, incluant des bornes municipales, des puits artisanaux, des forages dans des aquifères phréatiques, des forages dans des aquifères profonds et des *dhunge dharas* (sources publiques aménagées, qui captent les eaux souterraines ou de surface). Des informations ont été recueillies concernant les préférences des usagers ainsi que les caractéristiques du site et du puits, et l'eau a été analysée pour les indicateurs de contamination par les égouts, l'agriculture ou l'industrie. Les coliformes totaux et les bactéries *Escherichia coli* sont les plus problématiques, présents dans respectivement 94 et 72% des échantillons. La contamination par les nitrates, l'ammonium et les métaux lourds est plus limitée; 11 et 45% des échantillons excédant les normes népalaises en nitrates et ammonium, respectivement. Les concentrations en arsenic et en mercure étaient supérieures aux normes de l'OMS dans 7 et 10% des échantillons, respectivement, mais l'arsenic n'a jamais excédé la norme népalaise, moins stricte. Des différences importantes du niveau de contamination ont été notées entre les différents type de points d'eau ; les moins profonds de type puits artisanaux et dhunge dharas étaient affectés par les bactéries et les nitrates ; les forages dans les aquifères profonds étaient les plus contaminés par l'arsenic. Tandis que la concentration en *E. Coli* décroît avec la profondeur, les concentrations en fer et ammonium augmentent. Cette relation est importante, car des gens choisissent de boire une eau avec de fortes concentrations en bactéries, se basant plus sur l'apparence et l'aspect gustatif (non-métallique).

Resumen En el Valle de Kathmandu (Nepal), se muestreó agua de aproximadamente 100 puntos de agua, incluyendo llaves municipales, pozos excavados, sondeos en acuíferos someros, sondeos en acuíferos profundos y *dhunge dharas* (o surtidores de piedra, fuentes públicas de agua que suministran aguas subterráneas o superficiales). La información fue recogida según las preferencias de los usuarios y las características del punto y del pozo, y el agua se analizaron indicadores de contaminación de aguas fecales, agricultura o industria. El mayor problema fue el total de coliformes y las bacterias *Escherichia coli*, que estaban

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presentes en el 94 y el 72% de todas las muestras de agua, respectivamente. La contaminación por nitratos, amonio y metales pesados fue más limitada; los nitratos y el amonio excede las normas Nepalíes en el 11 y 45% de las muestras, respectivamente. El arsénico y el mercurio exceden las normas WHO en un 7 y un 10% de las muestras, respectivamente, pero el arsénico no excede en ningún caso las normas Nepalíes, menos estrictas. Existen diferencias significativas en los niveles de contaminación entre los tipos de puntos de agua; los pozos excavados y los dhunge dharas, como son los más someros, son los más contaminados por bacterias y nitratos; los sondeos de acuíferos profundos son los más contaminados por arsénico. Mientras que las concentraciones de *E. coli* descendieron con la profundidad, las concentraciones de hierro y amonio se incrementaron con la misma. Estas relaciones condicionan que la gente elija beber agua con un nivel alto de contaminación por bacterias debido a su mejor gusto (no metálico) y su apariencia.

Keywords Nepal · Kathmandu · Groundwater management · Urban groundwater · Contamination

Introduction

Like many developing countries, Nepal faces a plethora of problems regarding both its drinking water quality and availability. Throughout Nepal, people are exposed to severe health threats resulting from water contamination by sewage, agriculture, and industry. Owing to the impact of sewage, typhoid, dysentery, and cholera are endemic every summer (Khadka 1993). These diseases account for 15% of all illness and 8% of total deaths, but those numbers increase to 41% of all illness and 32% of all deaths in children up to 4 years old (Sharma 1990). In the Kathmandu Valley, the main urban center of Nepal, the chief concern is contamination from sewage lines, septic tanks, open pit toilets (Jha et al. 1997), and from surface water that has been polluted by direct disposal of sewage waste (Khadka 1992; Karn and Harada 2001). Nitrate contamination is also of concern. Currently, 90% of the Nepalese people are involved in agriculture; production must increase to meet the needs of the growing population even though most of the arable land is already under cultivation (Collins and Jenkins 1996). This has led to more intensive use of organic and inorganic fertilizers (Collins and Jenkins 1996), which leads to groundwater contamination with nitrate, among other materials. Surface water in Kathmandu Valley is also polluted with direct disposal of industrial waste, possibly leading to contamination of the shallow aquifer (Khadka 1992; Karn and Harada 2001). Approximately 50% of the water supply in the Kathmandu Valley is derived from groundwater sources (Jha et al. 1997; Khatiwada et al. 2002). Because of the insufficient municipal supply, fed by a combination of surface and groundwater, people use a variety of other groundwater sources including dug wells, tube wells and dhunge dharas (Khadka 1993).

Dhunge dharas (literally stone spouts or water taps) are the primary alternative to the municipal, piped water supply in the Kathmandu Valley (Conan 2004). They are located throughout the valley, both in dense urban and village settings. Dhunge dharas are historic and revered sources that derive much of their water supply from shallow groundwater (1–5 m below the ground surface) or from groundwater that may be artificially high because it is fed by shallow canals (Dixit and Upadhya 2005). In urban settings in Kathmandu, Patan, and Bhaktapur, dhunge dharas are usually located in low-lying areas and are excavated rectilinear brick-lined pits that tap the groundwater system and channel the groundwater to a spout or series of spouts. Some dhunge dharas, especially many built in the seventeenth century, bring water from a distant surface-water source or reservoir via a network of canals. Dhunge dharas in the valley periphery occasionally tap natural springs where water flows to the surface on terraced banks (Shrestha et al. 1996). Dhunge dharas have been used over the past 15 centuries; the oldest one known was built in 554 and is still in use today (Moench et al. 2003). The water from dhunge dharas is often considered to have religious significance and people generally consider the water clean enough to drink although some do boil or filter the water before drinking. The water is used for washing the body and face, drinking, healing, purification of deity images, and laundry (Becker-Ritterspach 1990).

There have been several previous studies of groundwater quality in the Kathmandu Valley. Khadka (1993) surveyed groundwater quality in dhunge dharas and springs, which revealed widespread sewage contamination based on indicator bacteria, pH, iron, and ammonia. Khadka also used three previous studies to compile results on water quality in deep-aquifer tube wells from several well fields within the Kathmandu Valley (Khadka 1992). Deep aquifer tube-well water contained high concentrations of iron, manganese, silica, dissolved ammonia, and carbon dioxide.

Nitrate contamination of groundwater was studied by Chettri and Smith (1995) in the cities of Bhaktapur and Patan in the Kathmandu Valley. Nitrate contamination was widespread in tube wells where 42% of the wells had nitrate levels above the old World Health Organization (WHO) limit of 45 mg/L (Chettri and Smith 1995). On the basis of the higher urban nitrate levels compared to those observed in tube wells in the agricultural Chitwan district, Chettri and Smith (1995) concluded that nitrate pollution from septic tanks and human waste was worse than the contamination problem posed by agriculture. In the cities, however, there was no apparent relationship between the nitrate levels in the wells and the distance of the water source to toilets (Chettri and Smith 1995).

In 1995, a joint program between the Australian Geological Survey Organisation (AGSO) and the Ground Water Resources Development Board (GWRDB) of Nepal conducted the most extensive evaluation to date of the groundwater quality in the Kathmandu Valley (Jha et al. 1997). Dug wells and shallow and deep-aquifer tube wells (but no dhunge dharas) were sampled both before and

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during the monsoon season and the water was analyzed for 30 chemical and microbial parameters, including heavy metals. Jha et al. (1997) determined that the shallow aquifer was extensively polluted by sewage with the highest levels of fecal contamination observed in the populated districts of Bhaktapur, Patan, and Kathmandu. Furthermore, there was an increase in fecal contamination during the monsoon season. They reported a coincidence of nitrate with fecal coliform bacteria, but presented no statistics confirming this relationship. Jha et al. (1997) found evidence for possible industrial contamination indicated by high ammonia concentrations in some shallow-aquifer wells and lead concentrations above WHO guidelines in 12 out of 75 wells. Although Khadka (1993) proposed that there might be industrial injection of wastes into the lower aquifer, Jha et al. (1997) found little evidence to support extensive industrial or sewage contamination at these greater depths.

All the previous studies highlight the severe groundwater-quality problems in the Kathmandu Valley and the need for more groundwater monitoring. No study to date, however, has systematically sampled water from a wide variety of sources, examined the water for possible indicators of sewage, agricultural, and industrial pollution, and attempted to relate the observed distribution to the well and/or site characteristics. The primary goal of this study is to look for relationships between site characteristics, people's water use and perceptions, and the degree of groundwater contamination. These relationships provide insights regarding the distribution of contamination and may help logically prioritize future water-quality improvement efforts. A water-quality survey was conducted in May and June 2001 in which drinking water was sampled from a variety of sources including dug wells, dhunge dharas, shallow-aquifer tube wells, deep-aquifer tube wells, and the municipal system. The water was tested for bacterial, inorganic, and trace-metal contamination. Specific research objectives included:

1. To identify common drinking-water contaminants thereby assessing the overall drinking-water quality in Kathmandu Valley
2. To quantify differences in water quality between the municipal system and supplemental water sources (dug wells, dhunge dharas, shallow and deep-aquifer tube wells)
3. To determine relationships between water quality and such site characteristics as depth of the well or proximity to toilets that could be used to predict a source's vulnerability to potential contamination
4. To determine the extent to which water users are choosing the better quality water, when faced with a choice of water sources

Regional setting

Nepal is a landlocked kingdom situated between China and India as shown in Fig. 1. The Kathmandu Valley is in the hill region of Nepal, an area of moderate elevation between the highlands of the Himalayan Mountains to the north and the Ganges plain to the south. The Kathmandu Valley, shown in Fig. 2, is a roughly circular intermontane basin with a diameter of 25 km and an average altitude of 1,350 m (above sea level); the surrounding hills are approximately 2,800 m in elevation. The average annual rainfall is 1.3 m, 80% of which falls during the monsoon season between June and September.

The bedrock underlying and surrounding the valley is composed of Paleozoic- and Precambrian-age rocks known as the Kathmandu Complex (Shrestha et al. 1996). To the south, limestone dominates, whereas to the east and west, the valley is bordered by phyllites and siltstones. Granite gneisses intrude into the rocks of the Kathmandu Complex that form the northern border of the valley (Shrestha et al. 1996). Overlying the bedrock formations are up to 500 m of Pliocene–Quaternary fluvial–lacustrine unconsolidated sediments (Yoshida and Igarashi 1984).

Hydrogeology

Within the unconsolidated sediments of the Kathmandu Valley, there are two major aquifers that provide residents with drinking water, as shown in the cross section in Fig. 3 (from Jha et al. 1997 and Cresswell et al. 2001). The upper aquifer is composed of up to 50 m of Quaternary arkosic sand, with some discontinuous, interbedded silt and clay of the Patan and Thimi Formations (Yoshida and Igarashi 1984). The surficial sediments that compose the upper aquifer are underlain by an aquitard of interbedded black clay and lignite that reaches up to 200 m in thickness in the western valley. The Pliocene sand-and-gravel, with interbedded lignite, peat, and clay, lies beneath the clay aquitard and constitutes the deeper confined aquifer used by several hotels, private companies, and municipalities (Jha et al. 1997).

Recharge of the deep aquifer occurs in the northeast part of Kathmandu Valley where the thick confining unit of clay is not present. Recharge rates have been estimated

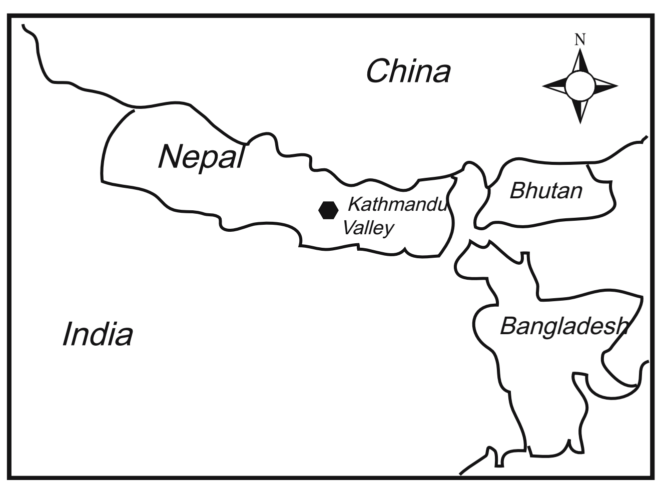

Fig. 1 Base map of Nepal with the Kathmandu Valley*highlighted*

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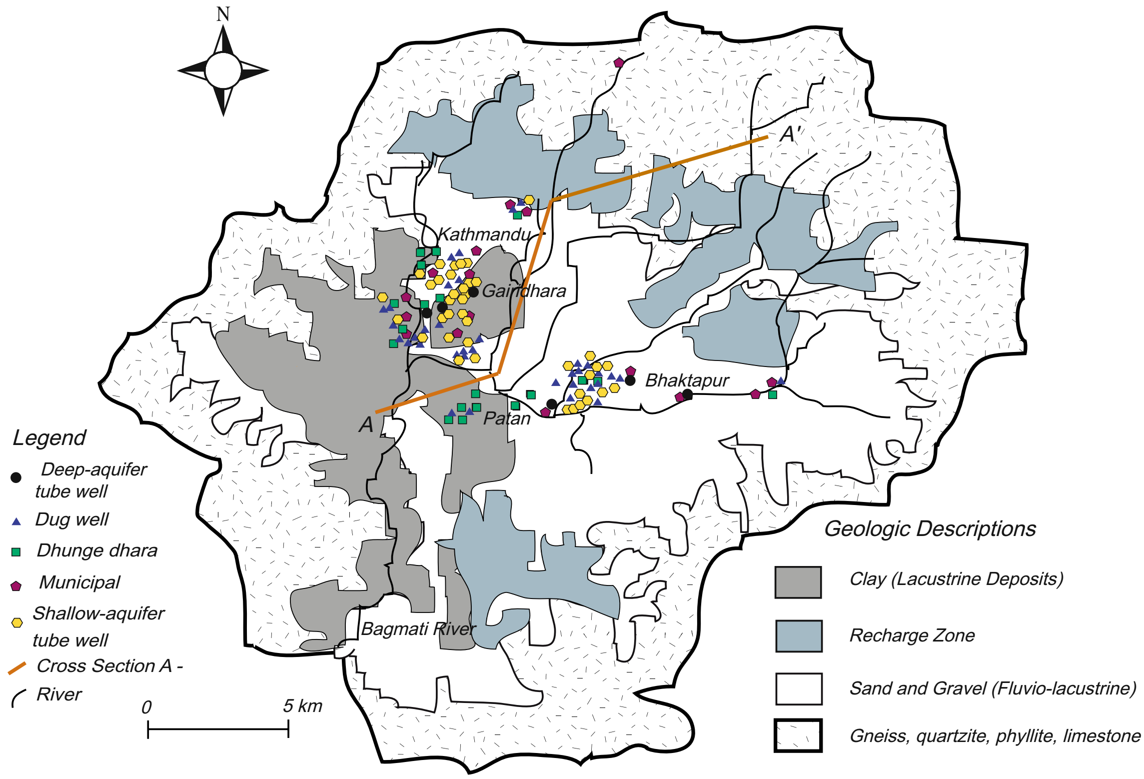

Fig. 2 Sample locations and geology within the Kathmandu Valley, adapted from Jha et al. 1997

to be between 13,000 and 40,000 m^3/day (Jha et al. 1997), but in a study using chlorine-36 isotopic analysis, Cresswell et al. (2001) determined that the recharge rate ranges only between 1,095 and 3,285 m^3/day, one twentieth of the current water-extraction rate estimated for the deep-aquifer by the Nepal Water Supply Corporation (NWSC; Dixit and Upadhya 2005). Assuming the latter estimate is correct, the deep-aquifer reserves will be depleted in less than 100 years (Cresswell et al. 2001); given the rapid growth of the Kathmandu Valley population, this may be an optimistic estimate.

Transmissivity values for the deep aquifer were estimated to vary from 83 to 1,963 m^2/day in the northern section of the valley and from 32 to 960 m^2/day in the

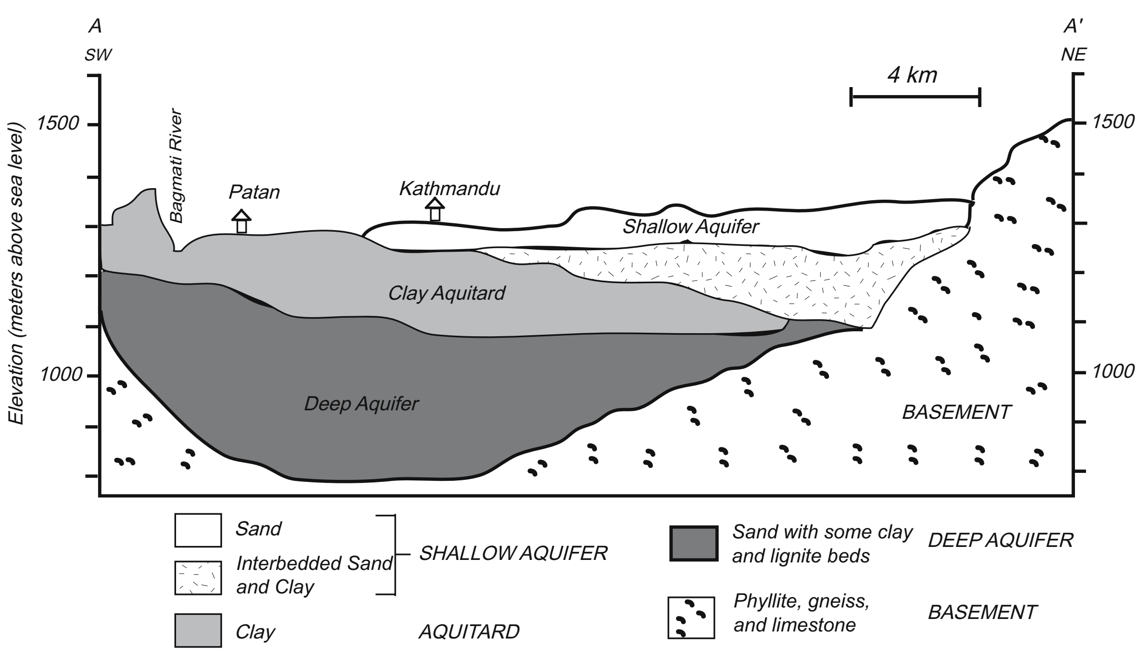

Fig. 3 Cross section through the Kathmandu Valley, with vertical exaggeration, adapted from Jha et al. 1997 and Creswell et al. 2001

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central portion of the valley where the majority of the population and therefore the majority of the private deep-aquifer wells are located (Dixit and Upadhya 2005). The potentiometric surface of the deep aquifer near the well fields of the NWSC dropped 15–20 m from 1985 to 1991 (Jha et al. 1997). Brown and Watkins (1994) observed that the productive capacity of older public tube wells has fallen, with some wells losing half their capacity between 1979 and 1987. In contrast, the shallow aquifer is recharged from direct infiltration of monsoon rains. Considering the slow recharge rate and subsequent limited sustainable supply of the deeper aquifer, it is critical to assess the potential for the shallow aquifer to meet both short- and long-term regional needs.

Domestic water use

Approximately 50% of the urban water supply in the Kathmandu Valley is derived from groundwater sources (Jha et al. 1997; Khatiwada et al. 2002) that tap either the shallow or deep aquifer. In 1992, the NWSC had 22 wells in operation, which withdrew 37,000 m^3/day from the valley. Another 13,000 m^3/day was extracted from private wells, 188 of which were shallow-aquifer tube wells and 146 of which were deep-aquifer tube wells (Jha et al. 1997).

The population of Kathmandu Valley in 2001 was 1.6 million with a projected growth rate of 5% (Dixit and Upadhya 2005). When the municipal system first came into operation in the 1970s, using a combination of surface water, deep-aquifer tube wells, and shallow aquifer sources (Khadka 1994), many communities abandoned their original sources of water, which included dhunge dharas, dug wells, and shallow-aquifer tube wells. The increasing population and the increased demand for water of about 200,000 m^3/day can not be met by the municipal supply which ranges between 85,000 and 130,000 m^3/day, for the dry and wet seasons, respectively (Dixit and Upadhya 2005). Consequently, water is often only available for 0.5–2 h each day (Khadka 1994; Dixit and Upadhya 2005). In addition, the quality of the municipal system is often poor owing to the poor condition of the distribution lines (Dixit and Upadhya 2005) and the proximity of water-distribution lines to sewage pipes. The sewage lines are often broken and under high pressure from overuse; in contrast, water distribution lines are under low pressure because they are over-drawn. As a result, old, leaky sewage lines allow waste to contaminate ageing, cracked water lines (Khadka 1994; Wolfe 2000).

The insufficient, intermittent and often polluted municipal water supply has driven numerous individuals and communities to supplement their water supply by tapping into their previous sources (Shrestha et al. 1996). Dhunge dharas are an especially important source of water for the middle- and low-income residents who cannot afford water from private-tanker companies. Unfortunately, with the introduction of the city water supply, many dhunge dharas were turned into refuse dumps and were not renovated prior to being brought back into use. Within Kathmandu Valley, people can therefore spend up to 45 min walking to the nearest dhunge dhara where they can wait in line for more than 6 h to fill their 15-L containers. Brown and Watkins (1994) estimated that 20% of the population of greater Kathmandu relies on dhunge dharas during much of the year for their water supply. With demand for water increasing, it is likely that an even larger fraction of the population will use dhunge dharas in the future.

Other sources of supplemental water include dug wells and shallow-aquifer tube wells. Dug wells are circular, shallow (less than 10 m), large diameter (1 m), inexpensive wells that are excavated by hand and usually partially lined with cement (Dongol et al. 2005). Shallow-aquifer tube wells are often drilled or bored by hand and are also generally shallower than 10 m. Some wealthier communities have drilled tube wells that are up to 200 m deep, capable of penetrating the deeper aquifer.

Sanitation, waste management, and chemicals of concern

Sanitation and waste management in the Kathmandu Valley is virtually non-existent. Karn and Harada (2001) report that Kathmandu generates 272,000 kg/day of solid waste, yet only 150,000–190,000 kg/day are collected. There are several landfill sites presently in operation; however, numerous uncontrolled sites are located throughout the valley, especially along the rivers (Shrestha et al. 1999) where the highly permeable sediments of the riverbed pose a pollution risk to groundwater. Currently in Kathmandu there is no wastewater treatment of an estimated 104 million L/day of wastewater (Karn and Harada 2001). There appears to be no regulation of industrial discharge of effluents into public sewers or onto land (Karn and Harada 2001). Personal sanitation in the developing neighborhoods is poor with several instances of drop-toilets co-located with the drinking water source for the household. When wells are not near a population center or household they are occasionally located near agricultural fields in which manure and chemical fertilizers are spread in excess quantities.

Given the waste disposal practices and breadth of contamination sources, a broad examination of possible contaminants from sewage, agriculture, and industry was necessary. Nitrate, nitrite, ammonia, phosphate, *Escherichia coli* (*E. coli*), and total coliform bacteria were examined as possible indicators of sewage contamination; manganese, iron, sulfate, and heavy metals were examined as indicators of domestic and industrial waste; and nitrate and heavy metals (i.e., arsenic and mercury) as possible indicators of agricultural contamination.

Methods

Water sampling

Water samples were collected from the Kathmandu Valley during May and June 2001, immediately prior to the monsoon season. Sampling locations are shown in Fig. 2. Water from a total of 115 sources was tested. Sources included six tube wells that penetrate the deep aquifer (deep-aquifer tube wells), 22 municipal sources, 16 dhunge dharas, 38 dug wells, and 33 shallow-aquifer tube wells. Locations for water sampling were chosen to represent a broad range of surface or well features throughout the valley.

Water samples were taken from the well, spout, or tap at each site. Whenever possible, water was kept running at tube wells and stone spouts for 2–3 min to purge the system before sampling. The running water continually flowed through a small bucket that contained an YSI datasonde that measured pH, dissolved oxygen, temperature, and specific conductance. Once the temperature stabilized, separate samples were collected for analysis of heavy metals (250 ml), bacteria (100 ml), and inorganic constituents (100 ml). At open dug wells, the datasonde was dropped down the well and submerged; samples were brought to the surface by the same method used by the owner. Municipal water samples were taken from family or community storage tanks on site or directly from taps at the municipal-treatment sites before distribution.

Water-source use, perception questionnaire, and site inspection

At each water-sampling site, a questionnaire was used to acquire information informally from water-source users regarding the source and its use. The questions were asked of people that happened to be present at the sources at the time of sampling (i.e., presently using the water source). Information gathered included the age of the well or tap, how many people use the source, how the water is used (drinking, washing, etc.), the availability of the municipal system in that area, and the presence of any industries in the immediate area. Questions were also asked concerning the users' perceptions of the water quality and their water-source preferences if they had choices. A visual inspection of the well and its surroundings was also conducted. Features such as depth of well, depth to water, well type, and distances to surface features such as toilets, agricultural fields, and surface-water bodies were measured whenever possible. Unfortunately, other information for these wells, including pumping-test or hydraulic conductivity data, was not available.

Water analysis

Bacterial contaminants

Using a sterile vacuum filtration device, 100 ml of the sample water were passed through a 0.1-μ filter. The filter was then placed in a Petri dish with m-Coli24-blue agar and placed in a warm environment out of the sun. The Petri dishes from each day's sampling were incubated at 35°C for 24 h. The agar contained an enzyme that caused the *E. coli* colonies (a type of fecal coliform) to turn blue, and the total coliform colonies to turn red. After 24 h, colony-forming units (CFUs) of *E. coli* and total coliform bacteria were counted. Owing to limited incubation space, only one sample was analyzed per site.

Inorganic contaminants

At each sampling site, a single water sample was collected and stored in a 250-ml low-density polyethylene (LDPE) bottle with zero head space for inorganic chemical analysis. Analyses for all samples collected in a day were performed at the end of the day using a DR-850 HACH portable, microprocessor-controlled, LED-sourced filter photometer. Water was examined for manganese, nitrate, nitrite, ammonia, sulfate, phosphorous, and iron as possible indicators of contamination using the specified colorimetric analyses for each constituent. All analyses were performed using the pre-programmed calibration curves for each contaminant (HACH 1999). The replicate-analysis standard deviation (HACH 1999) and the estimated detection limits for each constituent are shown in Table 1. In addition, 14 water samples were analyzed 3–4 times to estimate reproducibility. The reproducibility of the concentrations in the field equaled or exceeded the precision estimated by HACH (1999; Table 1).

Heavy metals

Separate water samples were also collected for heavy-metal analysis. These samples were placed without filtering in 250-ml LDPE bottles that had been previously treated with trace metal grade nitric acid diluted to 50% with double-deionized water for a period of 3 days. The bottles were sealed in double zipper-locked bags before and after sampling. The unfiltered water samples were returned to the United States and analyzed at Colgate University on a Hewlett Packard HP4500 inductively coupled plasma-mass spectrometer (ICP-MS). Seventy-five samples were analyzed for a suite of elements including Ni, Cu, Zn, Ga, As, Rb, Sr, Ag, Cd, Cs, Ba, Hg, Tl, Pb, Bi, and U. The ICP-MS was calibrated using a series of 10 external standards of these elements with concentrations ranging from 0.1 to 1000 μg/L; standard curves for all elements displayed Pearson correlation coefficients >0.992. The standard set was analyzed both before and after every set of 33 unknown water samples to verify consistency in instrument response and lack of signal drift.

Concentrations of the trace elements in each water sample were determined in triplicate; the reported values represent averages of the replicate analyses. Because the

Table 1 Upper and lower detection limits and estimated precision in the field using the portable HACH colorimeter

Contaminant	Lower detection limit	Upper detection limit	Estimated precision
NO_3–N	1	30	±2.0
NO_2–N	0.005	0.350	±0.01
NH_3–N	1	67	±5.0
Fe total	0.03	3.30[a]	±0.1
SO_4	5	80[b]	±3.0
PO_4^{3-}	0.05	2.50[a]	±0.1
Mn	0.12	20	±0.5

All units are shown in mg/L

[a] Upper detection limit often reached

[b] Upper detection limit reached twice

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samples were unfiltered, the reported concentrations are total metals and, therefore, conservative.

Statistical techniques

The degree of contamination was compared for different types of water source, community, water use, and the stated perceptions of water quality. To test for differences among populations and significance of correlations, the convention of Freedman et al. (1998) was adopted, where *p*-values less than 0.05 are statistically significant (thus providing moderate evidence against the null hypothesis) and *p*-values less than 0.01 are highly significant (thus providing strong evidence against the null hypothesis). By extension, *p*-values between 0.05 and 0.1 were considered to be weakly significant (providing weak evidence against the null hypothesis). All comparisons were performed using nonparametric statistics (Wonnacott and Wonnacott 1985). Such methods are considered robust and are based on the ranked data and are free of all assumptions regarding the distributions of the parameter values (Wonnacott and Wonnacott 1985). Nonparametric analyses are preferred when the data have many outliers and exhibit non-normal distributions. In addition, there were parameters (e.g., iron and phosphate) for which the measured values were the maximum value obtainable by the analytical technique. For these samples, the actual value was unknown but with nonparametric analysis, the data could still be used. All maximum values were assigned a rank equal to the average rank for all data tied at the maximum value. For example, if the 10 highest values out of a total of 50 data were at the maximum, each datum would receive a rank of 45.5.

To determine if there are any differences in contamination levels between the five drinking water sources in the Kathmandu Valley, rankings were compared using ANOVA (Snedecor and Cochran 1980). If there was a significant difference (at a p-value$\leq$0.05) in mean contaminant concentrations between all sources, individual differences between sources were investigated using Student's *t*-tests (Snedecor and Cochran 1980). Assessing differences among five water sources (i.e., dhunge dharas, dug wells, shallow-aquifer tube wells, municipal supply, and deep-aquifer tube wells), necessitates 10 pair-wise comparisons. Because 10 comparisons were made for each contaminant, a Bonferroni adjustment was employed in which the alpha level showing moderate evidence was reduced from 0.05 to 0.005. This adjustment is a conservative approach to ensure that the type-one error (i.e., incorrectly declaring a difference, effect or relationship to be true when the effect was due only to chance) for all the tests remains at 0.05. With nonparametric analyses, *p*-values are approximate but satisfactory (Wonnacott and Wonnacott 1985).

Correlation analysis was used to determine the relationship between site characteristics and contamination levels similar to the approach used by Conboy and Goss (2000). Correlation analysis in a heavily populated and highly polluted urban setting, such as the Kathmandu Valley, was thought to be potentially useful for identifying the major sources of pollution and establishing proper guidelines to reduce a well's vulnerability to contamination. For these analyses, ranked data were also used. Correlations with a p-value$\leq$0.05 were considered to be statistically significant.

Results and analysis

Well characteristics

Summaries of some well characteristics are presented in Table 2. Information for all tube wells was based on user-provided information, whereas total depth and depth to water in the dug wells was directly measured. For dhunge dharas, the total depth was estimated based on the distance of the tap below the ground surface. Based on the median values, dhunge dharas were the shallowest, followed by dugwells, and shallow-aquifer tube wells. Depth information was provided for only two wells in the deeper aquifer which were considerably deeper. Generally, dhunge dharas were the oldest sources tapping the shallow aquifer and the sources used by the most people. Of the 67 dug and drilled wells for which people responded, 45 were reported as having been installed within the past 5 years (median of 4.5 and 4.0 years for shallow-aquifer tube and dug wells, respectively). The two deep wells for which ages were given were reported as being 2.5 and 5 years old.

Bacterial contamination

The Nepali national drinking-water guidelines are provided in Table 3. The guidelines for total coliform and *E. coli* bacteria

Table 2 Summary of selected well characteristics

	Depth to water	Total depth	Source age	Number of users	Distance to toilet
	Shallow-aquifer tube wells				
Count	NA	32	34	34	31
Mean	NA	11.2	4.7	24.9	4.9
Median	NA	8.5	4.5	15	3.7
Minimum	NA	3.7	0.1	0.0	0.6
Maximum	NA	30.5	15	300	15.2
	Dug wells				
Count	36	36	33	34	31
Mean	4.4	5.7	28.9	66.2	6.1
Median	4.1	5.1	4.0	40	4.6
Minimum	0.84	0.84	0.1	0.0	0.3
Maximum	9.6	12.5	200	300	18.3
	Dhunge dharas				
Count	NA	12	14	13	11
Mean	NA	3.3	309	210	22.4
Median	NA	2.6	100	100	3.1
Minimum	NA	1.2	8	10	1.5
Maximum	NA	6.1	2,000	1,000	122
	Deep-aquifer tube wells				
Count	2	2	2	2	1
Mean	222	322	3.75	5,100	91.5
Median	222	322	3.75	5,100	91.5
Minimum	200	244	2.5	200	91.5
Maximum	243.9	400	5	10,000	91.5

Distances and depths are shown in meters; age is shown in years

NA Not Available

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Table 3 National Drinking Water Quality Standards, 2062 and National Drinking Water Quality Standard Implementation Guideline, 2062 Year: 2063 (B.S.) Government of Nepal, Ministry of Land Reform and Management Singhadurbar, Kathmandu, Nepal

Parameter or constituent	Unit	Maximum concentration limit
pH	pH units	6.5–8.5[a]
Specific conductance	mS/cm	1.5
$NO_3^- - N$	mg/L	11.3[b]
NH_3–N	mg/L	1.24[c]
SO_4^{2-}	mg/L	250
Al	mg/L	0.2
As	mg/L	0.05
Ca	mg/L	200
Cd	mg/L	0.003
Cu	mg/L	1
Cr	mg/L	0.05
Fe	mg/L	0.3
Pb	mg/L	0.01
Mn	mg/L	0.2
Hg	mg/L	0.001
Zn	mg/L	3
E. coli bacteria	CFU/100 ml	0
Total coliform bacteria	CFU/100 ml	0

[a] Levels are the minimum to the maximum

[b] Based on NO_3^- standard of 50 mg/L

[c] Based on NH_3 standard of 1.5 mg/L

CFU = colony-forming units

are zero detections in any 100-ml sample (Government of Nepal 2002). Water from 70 and 99% of all five types of water sources tested was contaminated (>1 CFU detected) with fecal and total coliform, respectively (Table 4). In general, total coliform levels were higher than *E. coli* levels for all sources. Some of the total coliform CFUs are most likely the result of benign bacteria that do not reflect sewage contamination of the groundwater and therefore total coliform CFUs were used only as a secondary indicator of contamination. Median concentrations of total coliform were highest for dug wells, followed by dhunge dharas, municipal supply, shallow-aquifer tube wells, and deep-aquifer tube wells. Although *E. coli* concentrations range as high as 800 CFU/100 ml, only about 5% of samples are above 200 CFU/100 ml. Dhunge dharas had the highest median *E. coli* concentrations, followed by dug wells, municipal sources, shallow-aquifer tube wells, and deep-aquifer tube wells.

Nonparametric *t*-tests were employed to determine which water sources were significantly different from each other in terms of bacterial contamination. It was hypothesized that the shallower and less-protected sources (dhunge dharas and dug wells) would be more contaminated by bacteria than deeper sources such as shallow-aquifer tube wells and deep-aquifer tube wells. Significant differences are presented in Table 5. As expected, dug wells were more contaminated by *E. coli* than both shallow and deep-aquifer tube wells; dhunge dharas were more contaminated by *E. coli* than shallow-aquifer tube wells. Concentrations of total coliform bacteria were higher in dug wells than in shallow-aquifer tube wells, deep-aquifer tube wells, and municipal sources.

Inorganic contamination

Table 6 compares concentrations of inorganic contaminants and other water-quality parameters in the five water sources. Dug wells and dhunge dharas are the most contaminated with nitrate, but generally have low levels of iron. The municipal supply, deep-aquifer tube wells, and shallow-aquifer tube wells have lower nitrate levels, but the highest iron levels. Deep-aquifer tube wells have the highest ammonia concentrations, but little nitrate.

The pH of sampled water ranged from 5.9 to 8.7. The Nepali national water quality standards require pH to be between 6.5 and 8.5 (Government of Nepal 2002). The pH was <6.5 in 51% of all sources, with the highest frequency in the tube wells (26 of 33) and deep-aquifer tube wells (1 of 1). The pH was >8.5 in 2 of 5 municipal sources. Specific conductance violated the Nepali standard of 1.5 mS/cm in just one source, a dug well with specific conductance of 1.56 mS/cm.

The Nepali national drinking-water quality standard and the WHO guideline for nitrate concentration in drinking water is 50 mg/L, (Government of Nepal 2002; WHO 2004) corresponding to 11.3 mg/L nitrate-N; only 11% of water samples contained concentrations at or slightly above this guideline and of those, the majority were only slightly above. The highest frequency of violations was found in dug wells (5 of 17). Nitrite concentrations were never above the WHO guideline of 3 mg/L (WHO 2004) in any of the sampled water (no Nepali standard for nitrite is available). The Nepali standard for ammonia of 1.5 mg/L was violated in 45% of the sampled sources with concentrations as high as 55 mg/L. Ammonia violations were most frequent in the relatively deeper sources like the shallow-aquifer tube wells (19 of 29) and deep-aquifer tube wells (4 of 5).

Table 4 Bacterial contamination in the five types of water sources

Source	No. of samples	*E. coli* (CFU/100 ml)					Total coliform (CFU/100 ml)				
		Min	Max	Mean	Median	Detected	Min	Max	Mean	Median	Detected
Dug well	37	0	800	100	28.5	86%	64	1,200	634	600	100%
Shallow-aquifer tube well	38	0	81	10	1	55%	1	1,000	269	103	100%
Municipal sources	19	0	750	70	12	76%	0	900	269	184	94%
Dhunge dhara	16	0	500	107	44	73%	14	1,000	423	400	100%
Deep-aquifer tube well	5	0	1	0.4	0	40%	1	91	43.2	41	100%

"Detected" denotes the percentage of samples detected ≥1 CFU/100 ml (above the Nepali drinking water standard)

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Table 5 Significant differences of bacterial concentrations among sources of water

Hypothesis	*p*-value	Strength of evidence
E. Coli		
Shallow-aquifer tube wells < dhunge dharas	0.0023	Moderate
Shallow-aquifer tube wells < dug wells	1.7×10^{-6}	Very strong
Deep-aquifer tube wells < dug wells	6.6×10^{-4}	Strong
Total coliform		
Shallow-aquifer tube wells < dug wells	2.0×10^{-7}	Very strong
Municipal sources < dug wells	9.9×10^{-6}	Very strong
Deep-aquifer tube wells < dug wells	4.0×10^{-5}	Very strong

There is no WHO guideline for iron content, but the Nepali drinking-water standard for iron is 0.3 mg/L or 3 mg/L when there are no alternative water sources (Government of Nepal 2002). Based on the colorimeter analyses, 64% of sources were at or above the 0.3 mg/L standard. Violations of the iron guideline occurred most frequently in deeper sources—24 of 26 shallow-aquifer tube wells and 5 of 5 deep-aquifer tube wells. Likewise, 58% of the sources violated the Nepali manganese standard of 0.2 mg/L, and again violations occurred most frequently in shallow-aquifer tube wells (18 of 26) and deep-aquifer tube wells (4 of 5). Sulfate concentrations never exceeded the Nepali standard of 250 mg/L although the upper detection limit was reached in water from two of the dug wells and one dhunge dhara. Phosphate values were highest in dhunge dharas, often at levels above the portable colorimeter's maximum detection limit of 2.75 mg/L.

As with total coliform and *E. coli* bacteria, it was hypothesized that dhunge dharas and dug wells would be more contaminated with nitrate than deeper sources such as shallow-aquifer tube wells and deep-aquifer tube wells. Significant differences are presented in Table 7. Dhunge dharas were more contaminated by nitrate than shallow and deep-aquifer tube wells and municipal sources; dug wells were more contaminated by nitrate than deep-aquifer tube wells. It was also hypothesized that dissolved iron contents would be higher in deeper sources due to less aerobic conditions. Dug wells and dhunge dharas had lower iron concentrations than shallow-aquifer tube wells (Table 7). Dhunge dharas also had lower iron concentrations than deep-aquifer tube wells and municipal sources.

Heavy metal contamination

No samples exceeded the Nepali water-quality standard for arsenic of 50 μg/L, as shown in Table 8. The WHO drinking-water arsenic guideline of 10 μg/L (WHO 2004) was exceeded in three of the six deep-well samples. Within the shallow aquifer, concentrations were highest in dug wells and dhunge dharas, but none exceeded either the Nepali or the WHO standards. Significant differences in arsenic concentrations existed between dhunge dharas and shallow-aquifer tube wells, dug wells and shallow-aquifer tube wells, and shallow-aquifer tube wells and deep wells.

Table 6 Inorganic contaminants and selected standard parameters in water sources within the Kathmandu Valley

	Mn	PO_4	Fe	SO_4	NO_3–N	NO_2–N	NH_3–N	Temp	SpCond	DO	pH
	Shallow-aquifer tube wells										
Mean	0.59	NA[a]	NA[a]	10	3.1	0.01	8.0	20.4	0.568	2.5	6.35
Median	0.60	2.3	3.3[a]	0.0	0.95	0.0	8.0	20.2	0.506	2.3	6.36
Minimum	0.0	0.12	0.0	0.0	0.0	0.0	0.0	18.2	0.152	0.26	5.90
Maximum	2.10	2.8[b]	3.3[b]	57	22	0.21	29	26.1	1.20	4.9	6.89
	Dhunge dharas										
Mean	0.33	NA[a]	NA[a]	25	8.4	0.018	1.0	19.8	0.592	3.4	6.52
Median	0.30	2.6	0.0	20	8.4	0.0090	0.0	19.9	0.528	5.1	6.59
Minimum	0.0	0.75	0.0	6.0	0.0	0.0	0.0	18.3	0.328	0.010	6.10
Maximum	1.4	2.8[b]	3.3[b]	80	26	0.088	7.0	21.5	0.938	6.6	6.84
	Municipal sources										
Mean	0.25	NA[a]	NA[a]	4.2	1.7	0.006	0.86	22.1	0.125	2.1	7.72
Median	0.0	1.1	0.37	2.0	1.0	0.0	1.0	22.0	0.110	1.0	7.89
Minimum	0.0	0.38	0.050	0.0	0.0	0.0	0.0	17.0	0.050	0.00	6.91
Maximum	1.0	2.8[b]	3.3[b]	20	6.7	0.025	3.0	26.0	0.205	6.2	8.70
	Dug wells										
Mean	0.22	NA[a]	NA[a]	36	6.9	0.025	2.4	19.5	0.827	1.99	6.61
Median	0.0	1.1	0.26	34	4.1	0.017	1.0	19.5	0.843	1.64	6.60
Minimum	0.0	0.35	0.0	0.0	0.0	0.0	0.0	18.4	0.308	0.0	6.10
Maximum	0.90	2.8[b]	3.3[b]	80	24	0.12	17	21.0	11.56	6.04	7.10
	Deep-aquifer tube wells										
Mean	0.88	NA[a]	NA[a]	0.20	0.14	0.007	27	26.2	0.959	NA	6.76
Median	0.80	2.8[a]	3.3[a]	0.0	0.0	0.0	16	26.2	0.959	NA	6.76
Minimum	0.0	0.27	1.1	0.0	0.0	0.0	0.0	25.8	0.923	NA	6.40
Maximum	1.9	2.8[b]	3.3[b]	1.0	0.70	0.029	55	26.6	0.994	NA	7.11

[a] *NA* not applicable. In the case of PO_4 and Fe concentrations, this is due to some concentrations reaching the maximum detectable limits

[b] Upper detection limit of Fe and PO_4

Mn Manganese, *PO_4* Phosphate, *Fe* Iron, *SO_4* Sulfate, *NO_3–N* Nitrate, *NO_2–N* Nitrite, *NH_3 –N* Ammonia, *Temp* temperature, *SpCond* specific conductance, *DO* dissolved oxygen. All units are mg/L except for temperature (°C) and specific conductance (mS/cm)

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Table 7 Significant differences in nitrate and iron concentrations among sources of water

Hypothesis	*p*-value	Strength of evidence
Nitrate		
Shallow-aquifer tube wells < dhunge dharas	5.1×10^{-4}	Strong
Deep-aquifer tube wells < dhunge dharas	2.0×10^{-5}	Very strong
Deep-aquifer tube wells < dug wells	0.0030	Moderate
Municipal sources < dhunge dharas	1.9×10^{-4}	Strong
Iron		
Dhunge dharas < shallow-aquifer tube wells	1.5×10^{-7}	Very strong
Dug wells < shallow-aquifer tube wells	9.6×10^{-5}	Very strong
Dhunge dharas < deep-aquifer tube wells	2.8×10^{-5}	Very strong
Dhunge dharas < municipal sources	8.2×10^{-4}	Strong

In the case of mercury, the Nepali drinking-water standard of 1 μg/L (Government of Nepal 2002) is stricter than the WHO guideline of 2 μg/L (WHO 2004). Both guidelines were violated in two deep wells, one dug well and two shallow-aquifer tube wells (Table 8). Mercury concentrations did not differ significantly among any of the drinking water sources.

Zinc concentrations exceeded the Nepali drinking-water standard of 3 mg/L in 1 of 16 dug wells and none of the other sources. All other heavy metals, including Ni, Cu, Ga, Rb, Sr, Ag, Cd, Cs, Ba, Tl, Pb, Bi, and U, were detected in low concentrations, well below the Nepali and WHO guidelines and are therefore not discussed further.

Effect of community age and type

Depending on the microbiological and chemical stability of a contaminant, the concentrations in groundwater could increase over time because of continued contamination. Higher levels of contaminants would most likely be found in older communities than in the newly developed areas (Chettri and Smith 1995). The influence of the type and density of a community on the degree of water contamination may also provide insights into the causes of contamination (Chettri and Smith 1995). Contamination in tube wells, dug wells, and dhunge dharas in communities ten years old or less (most often rural/suburban areas with some agriculture) and older communities (often denser suburban/urban areas) was compared. Applying a nonparametric, ranked test, there was moderate evidence that total coliform bacteria and *E. coli* values were significantly higher in the older urban communities than in the newer, suburban communities (p-values=0.026 and 0.016, respectively) suggesting the sewage systems in the newer communities do a better job at protecting water supplies. No such evidence was found for iron, manganese, nitrate, ammonia, or any of the heavy metals.

Relationship of shallow aquifer contamination to other site characteristics

For water sources tapping the shallow aquifer, nonparametric, ranked correlation analysis was used to explore relationships between contaminant concentrations and site characteristics including the water source's total depth, depth to water, and distance from the nearest toilet or septic system. Generally, the deeper the source, the less susceptible it is to contamination. *E. coli*, nitrate, and arsenic concentrations all decreased with increasing total depth of the well or dhunge dhara. Correlation coefficients for *E. coli*, nitrate and arsenic were –0.35, –0.54 and –0.42, respectively, all significant at $p\leq0.005$ (Table 9). Iron and ammonia concentrations, on the other hand, increased with depth (correlation coefficients=0.68 and 0.36, respectively with respective p-values<0.001 and 0.011; Table 9). Other potential contaminants were not significantly correlated to the source's total depth.

The relationship between depth to water and contaminant concentration was investigated using dug wells and tube wells. No significant correlations were found.

To establish proper guidelines that may reduce a well's vulnerability to contamination from sewage, it is important to determine if there exist relationships between the distance from sewage systems and the degree of contamination of water sources. Examining dhunge dharas, dug wells and tube wells in the shallow aquifer, there were no significant relationships between total coliform or *E. coli* concentrations and the distance to the nearest toilet or septic system. Phosphate concentrations, on the other hand, decreased with increasing distance (correlation coefficient=–0.36, p=0.024; Table 9). When the analysis was repeated with just dug wells, both nitrate and phosphate concentrations decreased with distance from a sewage source (correlation coefficients=–0.56 and –0.68, respectively; p=0.047 and 0.014, respectively; Table 9).

Table 8 Heavy metal concentrations for the five drinking water sources

Source	No. of samples	Arsenic (μg/L)					Mercury (μg/L)				
		Min	Max	Mean	Median	Above limit	Min	Max	Mean	Median	Above limit
Dug well	16	0.38	6.0	1.3	0.74	0%	0.0	5.8	0.72	0.47	6.3%
Shallow-aquifer tube well	23	0.20	3.9	0.62	0.34	0%	0.0	7.3	0.64	0.020	8.7%
Municipal source	12	0.22	2.2	0.93	0.57	0%	0.0	0.83	0.21	0.16	0%
Dhunge dhara	13	0.30	4.0	1.1	0.97	0%	0.0	1.3	0.23	0.04	0%
Deep-aquifer tube well	6	0.13	21	12	11	50%	0.0	2.6	0.97	0.46	33%

Number of samples above the limit was based on the WHO standard of 10 and 1 μg/L for arsenic and mercury, respectively

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Table 9 Relationships between site characteristics and contaminant concentrations

Site characteristic	Contaminant	Correlation coefficient	*p*-value	Number and type of sources used
Total depth	*E. coli*	−0.35	0.002	34 dug wells, 32 tube wells, 12 dhunge dharas
Total depth	Fe	0.68	<0.001	17 dug wells, 20 tube wells, 10 dhunge dharas
Total depth	Nitrate	–0.54	<0.001	17 dug wells, 20 tube wells, 10 dhunge dharas
Total depth	Ammonia	0.36	0.011	17 dug wells, 23 tube wells, 10 dhunge dharas
Total depth	Arsenic	–0.42	0.004	16 dug wells, 20 tube wells, 10 dhunge dharas
Distance to sewage source	Phosphate	–0.36	0.024	12 dug wells, 19 tube wells, 8 dhunge dharas
Distance to sewage source	Phosphate	–0.68	0.014	12 dug wells
Distance to sewage source	Nitrate	–0.56	0.047	13 dug wells

Correlations determined using ranked, nonparametric analysis. Only sources from the shallow aquifer were used

Questionnaire results: relationship of contamination to people's choices and perceptions

Interviews either with the owner(s) or user(s) of the water source were conducted at 15 dhunge dharas, 35 dug wells, 36 tube wells, 2 deep wells and 3 municipal sources as shown in Table 10. Perhaps partly because of their history, all of the dhunge dharas were reported to be used for drinking, and all of the interviewees at the dhunge dharas felt that water from dhunge dharas was safe to drink. On the other hand, 61% of shallow-aquifer tube wells and 43% of dug wells in this survey were not used for drinking but were used only for washing clothes and dishes. Reasons given by interviewees for not drinking the water included a bad smell, cloudy appearance, or unsavory taste to the water. The municipal system was used for drinking in all three of the sites where the owner was surveyed.

It is important to assess whether people are making a healthy choice when they have several options for their drinking-water source. They may be making their choices on the basis of taste, rather than on health risks. It was hypothesized that the reported bad taste was associated with higher iron concentrations. Water with high iron concentrations is often considered unpalatable in terms of taste, odor, appearance, and ability to discolor food (Edmunds and Smedley 1996). To test this hypothesis, the ranked iron concentrations in sources with water reported as potable (mean rank=22.0) were compared with sources with water reported as not used for drinking (mean rank=40.9, out of a total of 59 ranked sources; Table 10). Using a nonparametric, ranked t-test, the hypothesis was very-strongly supported ($p=2.38\times10^{-6}$).

Dhunge dharas were generally more trusted for drinking and, as shown above, were more contaminated with respect to *E. coli* than tube wells and more contaminated by nitrate than any source other than dug wells. These relationships led to the hypothesis that water that was perceived as being not suited for drinking may actually be cleaner with respect to bacteria and nitrate; therefore, people might be unknowingly choosing poorer-quality water to drink. A nonparametric t-test indicated there was moderate evidence ($p=0.033$) that *E. coli* bacteria were more abundant in water from sources identified as being good for drinking (mean=77.6 CFU/100 ml) versus water identified as not good for drinking (mean=49.2 CFU/100 ml; Table 10). Likewise, there was very strong evidence ($p=0.00011$) that nitrate concentrations were higher in water from sources identified as being good for drinking (mean=7.7 mg/L) versus water identified as not good for drinking (mean=1.7 mg/L; Table 10). It appears

Table 10 Comparison of water described as suitable for drinking and water described as not suitable for drinking

	All surveyed	Perception		Significance of difference (*p*-value)[a]
		Suitable for drinking	Not suitable for drinking	
Total number	91	53	38	NA[b]
Number of deep wells	2	1	1	NA
Number of dhunge dharas	15	15	0	NA
Number of dug wells	35	20	15	NA
Number of shallow-aquifer tube wells	36	14	22	NA
Number of municipal sources	3	3	0	NA
Mean rank of Fe concentration[c]	29.5	22.0	40.9	2.4×10^{-6}[d]
Mean total coliform concentration (CFU/100 ml)	422	416	431	0.46
Mean *E. coli* concentration (CFU/100 ml)	61.4	77.6	49.2	0.033[d]
Mean NO_3^- concentration (mg/L)	5.31	7.68	1.70	1.1×10^{-4}[d]
Mean As concentration (µg/L)	1.4	1.4	1.5	0.064
Mean Hg concentration (µg/L)	0.60	0.44	0.87	0.25

[a] Based on a nonparametric t-test using ranks

[b] No statistical test applied

[c] Ranks are presented rather than means because some of the iron concentrations were at the maximum detection limit of 3.3 mg/L

[d] Differences that are significant at a *p*-value of 0.05 or lower

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that much of the best water in terms of low bacterial and nitrate contamination is not being used for drinking due to the poor aesthetic qualities that high iron concentrations create. Based on similar nonparametric tests, there was no significance difference between perceived potable and nonpotable water in terms of arsenic, mercury or total coliform concentrations (Table 10).

Other factors

Many well characteristics and nearby surface features were examined using the same statistical techniques as mentioned above that did not produce any statistically significant relationships. Some of these factors included: well age, toilet type (e.g., septic or sewer), distance from the water source to the toilet, the number of people using the water source, distance to surface water, building density/presence in the area, community age, industry density, method of water extraction, and presence of nearby agriculture.

While enquiries were made regarding the distance to the nearest toilet, there was no means by which one could determine the hydraulic gradient at each source, so it was not possible to determine whether toilets were up or down gradient. It is reasonable to assume, however, that in many of the areas, dhunge dharas (where water continually flows) and wells (due to withdrawals) represent local potentiometric lows so nearby toilets are likely to be up-hydraulic gradient.

Discussion

Probable sources of heavy metal contamination

Arsenic

Elevated concentrations of heavy metals such as arsenic, can be indicators of industrial contamination, but often high concentrations of arsenic in groundwater are from natural sources. Results from this study indicate that arsenic contamination of water in the Kathmandu Valley is not a major concern. Of all the water sources tested, none had arsenic concentrations greater than the Nepali standard of 50 μg/L and only three sources, all in the deep aquifer, had arsenic concentrations above the WHO guideline of 10 μg/L. Interestingly, there was evidence that arsenic concentrations in the shallow aquifer decreased with depth, but the predominance of arsenic in the deep aquifer in combination with the low levels of other heavy metals suggests that the arsenic is not of an industrial origin within the Kathmandu Valley and may be from a natural source similar to that in the Terai region of Nepal as discussed by Panthi et al. (2006).

Mercury

Mercury levels above the Nepali standard occurred in two shallow-aquifer tube wells, one dug well, one dhunge dhara and two of the deep-aquifer wells. Three of the water sources with mercury levels greater than 1 μg/L were in the same community of Gairidhara, suggesting that mercury contamination might have been from a localized source, either natural or industrial. Elevated mercury concentrations within the Kathmandu Valley were first reported by Khatiwada et al. (2002) who found water sources with elevated mercury in 23 out of 31 sources, including some deep-aquifer wells. The exploration of a possible source to the mercury is beyond the scope of this investigation, but Khatiwada et al. (2002) indicated at least one sample with elevated mercury was most likely from a nearby industrial source.

Water management implications and recommendations for future use

Water samples from the deeper, confined aquifer in the Kathmandu Valley were relatively free of bacterial contamination compared to those from the shallow aquifer. There were very few fecal bacteria found in any of the five samples from the deeper aquifer. The use of water from the deep aquifer is a logical alternative to the heavily polluted shallow aquifer. The fact that there was any fecal bacterial contamination of the deep aquifer water raises the question of how that can be; given the depth, slow recharge rate, and the relatively old age (200,000–400,000 years) of the water (Cresswell et al. 2001). One possibility is contamination at the wellhead due to improper well construction or deterioration of the well. Another possibility is that the distribution and storage system has been contaminated. This possibility is illustrated anecdotally by sampling at one of the deep-aquifer well sites at Lokanthali. The well sampled there was a municipal well, and an opportunity arose to sample the water before and after the water treatment process. Water sampled before treatment right from the well head had no *E. coli* and 1 CFU/100 ml total coliform bacteria (as included in Table 4). After water treatment, *E. coli* and total coliform concentrations of 4 and 900 CFU/100 ml were measured, respectively. Obviously, the water was being contaminated after being brought to the surface either in the settling tanks, transport pipes, or storage tanks, a phenomenon also noted by Khadka (1992).

The elevated arsenic concentrations in the samples from the deeper aquifer are slightly above the WHO guidelines but below the Nepali standards and are not as serious a health threat as the widespread bacterial contamination in the shallow aquifer and should therefore not necessarily discourage the use of the deeper aquifer as a drinking water source. The slow rate of recharge to the deep aquifer (Cresswell et al. 2001), however, limits its use as a long-term sustainable solution to the drinking water needs of the Kathmandu Valley.

Despite its extensive contamination, the shallow aquifer will still have to be used as a drinking-water source until other sources are developed. It will be necessary, of course, to find affordable treatment methods for water from the shallow aquifer, which could provide residents with an adequate supply of safe drinking water. Water from tube

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wells with high iron concentrations could be passed through inexpensive sand and charcoal filters to decrease iron concentrations. It is likely that as a free public source of water, dhunge dharas will continue to be relied upon as a drinking water source. Bacterial contamination levels in dhunge dharas could be remedied with a UV purification system or by filtration.

Conclusions

As shown in several previous studies, the water in the shallow aquifer of the Kathmandu Valley is polluted with fecal coliform bacteria (Jha et al. 1997; Khadka 1993, 1994; Wolfe 2000). The shallow aquifer has been used extensively by many of the local residents and poses a serious risk to those who use the water without adequate treatment. Bacterial indicators are present in every drinking water source; at present, the most serious threat to health is from water-borne diseases caused by inadequate sewage disposal (Karn and Harada 2001). Nitrate contamination, most likely from both sewage and agriculture, is also common in the shallow aquifer but at concentrations only slightly higher than the WHO guidelines in 11% of the water sources sampled, is not an immediate health concern for the majority of the population.

The deep-aquifer tube wells were the least contaminated with bacteria and nitrate. Within the shallow aquifer, tube wells exhibited the least bacterial and nitrate contamination of any drinking water sources whereas dug wells and dhunge dharas possessed the most. The municipal system, in general, was intermediate in terms of contamination levels and often not significantly different from other sources.

Arsenic levels were above the WHO guidelines in the deeper aquifer in three of the six sampled sources; the Nepali standard was not violated in any of the samples. Based on the distribution of the arsenic contamination and its lack of association with other metals, it is likely the result of natural conditions within the deep aquifer rather than industrial contamination. Further examination of the distribution and concentration of arsenic within the deep aquifer would be advisable, but the concentrations analyzed in this study do not indicate an imminent health threat to deep-aquifer users. Mercury levels were above the WHO guidelines in three of the sources tapping the shallow aquifer as wells as two of the deep-aquifer wells. The clustered distribution of the contamination suggests a local, perhaps industrial source. Other heavy metals (Ni, Cu, Zn, Ga, Rb, Sr, Ag, Cd, Cs, Ba, Tl, Pb, Bi, and U) all have concentrations below the WHO and Nepali guidelines. Based solely on heavy-metal occurrence, there is little evidence of widespread industrial contamination of the shallow aquifer; however, no analyses were performed for organic contaminants that might be better indicators of widespread pollution in the valley.

Within the shallow aquifer, the degree of contamination by bacteria, nitrate and arsenic was significantly related to the total depth of the water source. Sources at greater depth were less likely to be contaminated. Iron concentrations, on the other hand, increased with depth. The degree of contamination was also related to the source's distance from sewage systems. In all types of shallow-aquifer sources, phosphate concentrations decreased with increased distance to toilets or septic tanks. For just dug wells, both nitrate and phosphate concentrations decreased with increased distance from sewage or septic system toilets. No such correlations were found for bacterial contamination.

In general, wells have higher levels of bacterial contamination in the older communities, possibly due to a longer period of contamination or sewage systems in a greater state of disrepair. Younger communities, on the other hand, had higher levels of nitrate contamination, most likely due to the influence of nearby agriculture.

Based on surveys of water-quality perceptions, water sources were divided into those used for all purposes including drinking and those that were not used for drinking. The choice might have been due in part to the iron concentration in the water; water used for drinking had significantly less iron. Unfortunately, *E. coli* and nitrate concentrations were higher in the water used for drinking. These relationships are easily explained. People generally preferred getting their drinking water from dhunge dharas, the shallowest of all the sources. Shallower sources were found to be more contaminated by bacteria and nitrate and have less iron than deeper sources.

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