Assessment of the chemical quality of drinking water in Cambodia

Peter R. Feldman, Jan-Willem Rosenboom, Mao Saray, Peng Navuth,
Chea Samnang and Steven Iddings

ABSTRACT

Most water supply programmes in Cambodia have focused on providing access to bacteriologically safe water, an approach which has led to an increasing reliance on ground water, especially in rural areas. However, there have been very few data collected on the chemical quality of the nation's drinking water sources, and few water supply programmes have the capacity to assess chemical quality. The study was designed to address this data gap by conducting a low-cost, rapid assessment of drinking water sources nationwide to determine whether there were any chemicals of concern in Cambodian water supply sources. Results of the assessment confirm that there are several parameters of health and aesthetic concern; dissolved arsenic is the most significant. Elevated arsenic levels (some exceeding 500 $\mu g\, l^{-1}$) were detected in aquifers of moderate depth in several highly populated areas, confirming that further investigation of the occurrence of arsenic contamination in Cambodia is warranted. Other chemicals of health concern include nitrate, nitrite, fluoride and manganese. Additionally, many ground water sources are negatively impacted by parameters of aesthetic concern, such as iron, manganese, hardness and total dissolved solids. Elevated levels of these parameters have caused consumers to reject newly installed water supplies, often in favour of surface water sources that are bacteriologically unsafe.

Key words | arsenic, Cambodia, drinking water, health, water quality

Peter R. Feldman (corresponding author)
Plan International Cambodia,
PO Box 1280, Phnom Penh,
Cambodia
E-mail: *feldman@online.com.kh*

Jan-Willem Rosenboom
World Bank Water and Sanitation Program,
PO Box 1115, Phnom Penh, Cambodia
E-mail: *jrosenboom@worldbank.org*

Mao Saray
Chea Samnang
Ministry of Rural Development,
Phnom Penh, Cambodia
E-mail: *maosaray@online.com.kh*,
cheasamnang@online.com.kh

Peng Navuth
Ministry of Industry, Mines, and Energy,
Phnom Penh, Cambodia
E-mail: *navuth@camshin.com.kh*

Steven Iddings
World Health Organization,
Suva, Fiji
E-mail: *iddingss@sp.wpro.who.int*

INTRODUCTION

The Kingdom of Cambodia, a nation of nearly 14 million, struggling to revitalize its economy and infrastructure after decades of war and civil conflict, is burdened by some of the highest levels of poverty and disease in the region. Cambodia's under-five mortality rate of 124 per 1,000 live births is the second highest in Asia, and nearly 40% of the population lives on less than one dollar per day (NIS 2003; UNICEF 2004). As water-related diseases are among the leading causes of morbidity and mortality among Cambodian children, provision of safe water is a high priority for the Royal Government of Cambodia (MEF 2004; WHO 2004*a*).

Efforts to improve drinking water supplies undertaken since the early 1980s have been moderately successful in urban areas, as the proportion of urban residents with access to safe water is estimated to exceed 70% nationally (NIS 2004) and may exceed 85% in Phnom Penh (NIS 2002). (In Cambodia the term 'safe water' typically means piped water, water obtained from drilled wells with hand-operated or powered pumps, or water obtained from concrete-lined hand-dug wells. Though the bacteriological safety of any of these sources can reasonably be questioned, most agencies consider these sources 'safe' as a working definition.)

However, among Cambodia's rural population (who constitute 84% of the total population), only 34% are estimated to have access to safe water (NIS 2004). Most

doi: 10.2166/wh.2006.048

rural residents access surface or shallow ground water sources that are bacteriologically contaminated. The government and many of its partner agencies have been implementing programmes to install ground water wells as a means of providing year-round water supplies that are bacteriologically safer than those currently available. The actual number of rural water supply wells in Cambodia is not known, although anecdotal evidence from the Ministry of Rural Development and other agencies suggests that the number of public and private wells has increased rapidly within the past ten years.

Though wells installed by the government and its partners were intended to provide bacteriologically safe drinking water, the chemical quality of the water they provided had not been systematically characterized prior to this assessment, which was completed in January 2001. The assessment was conducted by the Ministry of Rural Development and the Ministry of Industry, Mines, and Energy, and was supported technically and financially by WHO. The assessment was designed to rapidly determine whether Cambodia faced any chemical water quality problems that were of significant public health concern. In addition, it was intended to provide a body of data to serve as a baseline for comparison with future water quality studies.

The assessment focused exclusively on chemical water quality. Though significant to human health, microbiological parameters were not included in this study for several reasons: 1) sector professionals in Cambodia were already well aware of the threat of microbiological contamination; 2) many bacteriological tests had already been performed on Cambodian drinking water sources and local capacity for this existed; 3) performing bacteriological tests on the sampled water sources would have greatly increased the time, staff, equipment and budgetary requirements of the project. The scope of the assessment was therefore kept purposefully narrow so as to focus the limited available resources on an issue that had received little prior attention.

The assessment was executed over a 12-month period and provided new information regarding Cambodia's drinking water quality situation, including identifying arsenic as a potentially significant public health issue. Results of the assessment have led or contributed to a number of follow-up actions by the government, including the promulgation of national drinking water quality standards, further investigation of arsenic occurrence and mitigation techniques, and a reassessment of the technical and policy approaches being used to solve the nation's urgent drinking water supply problems.

METHODS

Study area and sample locations

The study area comprised 13 of Cambodia's 20 provinces and contained approximately 80% of the total population. The study area did not include the municipality of Phnom Penh, as much of the capital is served by a large water treatment and distribution system.

Budget and time constraints permitted collection and analysis of approximately 100 samples during the first and main round of sampling. Excluding duplicates and trip blanks, this resulted in the collection of 94 unique samples during the 'main' round of sampling. (A portion of the budget was reserved to conduct follow-up sampling should further clarification or confirmation of any findings be needed, which also reduced the size of the main round of sampling.) The limited number of samples meant that the sampling density was relatively thin, but given the fairly uniform geography of much of central Cambodia, it was decided it would be more worthwhile to screen a larger area rather than focusing in more detail on a smaller portion of the country. If the highly populous area of the country had been more geographically and geologically diverse, a greater number of samples would probably have been required to accomplish the same task.

A total of seven or eight samples were collected from each province within the study area. Within each province, one sample was obtained from the public water supply system in the provincial capital, and the balance of samples was collected from rural drinking water sources.

Samples were collected during the dry season, which permitted greater access in rural areas, as well as making it more likely that ground water sources used for drinking on a seasonal basis would be in regular use. A small number of samples were also collected from perennial surface water bodies that served large numbers of rural residents, even during the dry season. The study area and sample locations are shown in Figure 1.

The originally designed sampling strategy had to be modified during the early phases of the study. The original plan called for the compilation of a database of existing wells in each province and use of this database to guide the sampling effort. Samples would be collected from different areas of ground water exploitation within each province, and to the extent feasible, samples would be collected from wells of varying ages and depths. However, in practice, the available data on supply wells was incomplete and often out of date. Sample locations chosen using the database often proved to be out of service or otherwise unsuitable, or the location data were inadequate to actually locate the desired sampling points.

A modified sampling strategy was then developed in consultation with government project partners. To promote greater involvement in the study at the local level, the sampling team discussed the sampling approach at a meeting held on entry into each new province. Officials from the provincial Department of Rural Development and the Department of Industry, Mines and Energy participated in these discussions, and they were often joined by Health Department officials as well. The goals of the study were explained, and the officials were encouraged to provide input into the selection of sampling areas. The selection process sought to spread the samples geographically throughout the most populous areas of each province; however, local authorities were also encouraged to recommend particular areas for sampling if they were aware (or suspected) that water quality problems existed there. Given the small number of samples available, the sampling team hoped to make as much use of local knowledge of water quality conditions as possible.

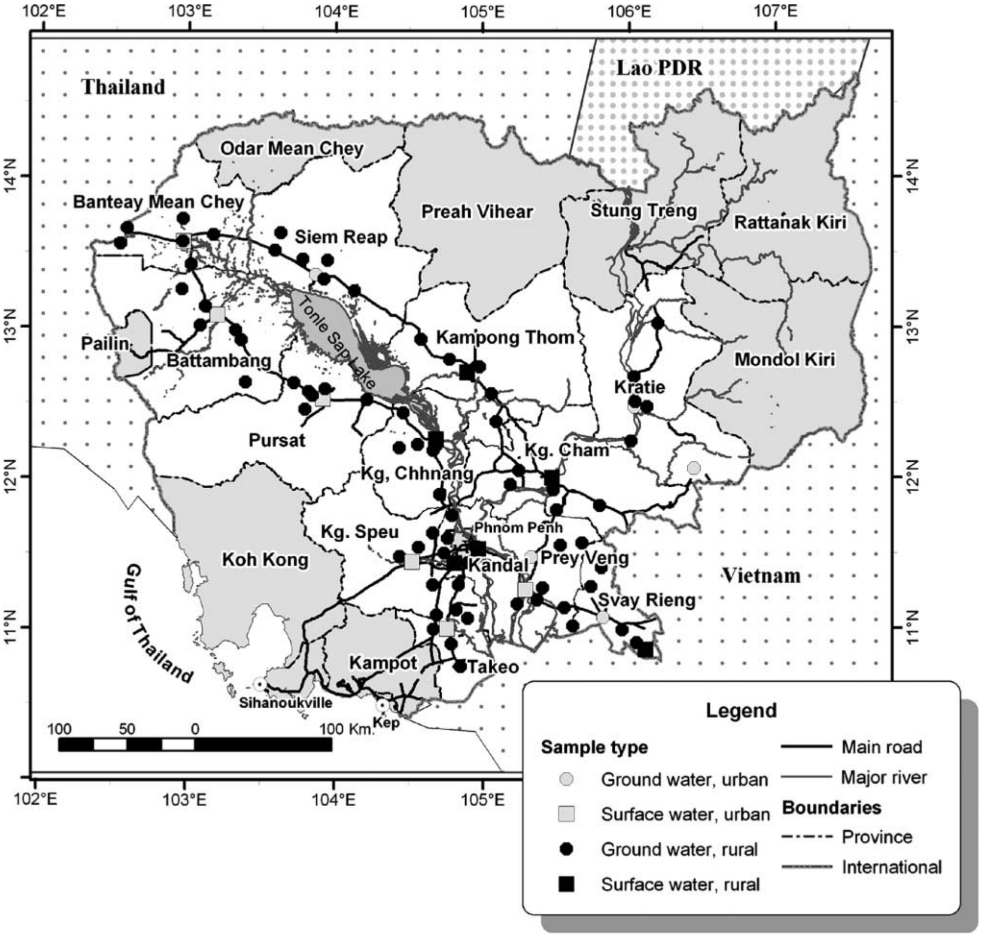

Figure 1 | Study area and sampling locations.

The main disadvantage of this sampling strategy is that the samples were not collected in a truly randomized fashion and, as a result, certain significant local conditions might have been overlooked or overemphasized. The chief advantages of the strategy were that it allowed the sampling team to quickly identify the principal areas of ground water exploitation within each province, and it allowed local officials to play a role in targeting areas where drilling or earlier water quality tests had suggested potential water quality problems.

Urban samples generally were collected from a tap at the water treatment plant itself, during a visit that included a brief inspection of the treatment system and interviews with staff and management. Rural samples were collected primarily from drilled boreholes equipped with hand-operated pumps. Nearly all of these were community wells installed as part of government or international assistance programmes, and were typically serving from 10 to 20 families each. All water sources sampled for this assessment were in use as drinking water supply sources at the time of sampling.

The follow-up sampling budget enabled confirmation of significant findings that came out of the main round of sampling. Twenty-one follow-up samples were collected for heavy metals analysis following the identification of what appeared to be an area with high concentrations of arsenic. The follow-up samples included a reconfirmation of two earlier arsenic 'hits', as well as a number of public and private wells in the suspected arsenic hot spot (the prevalence of private family wells in this area meant that a smaller number of community wells were sampled than in the previous round). Table 1 summarizes the water sources sampled during the assessment.

Field methods

Samples were collected in the field from wells, taps or other points used by local residents. Pumps and taps were operated or run for at least five minutes prior to sampling to ensure collection of a representative sample (temperature and electrical conductivity were monitored to verify this). Each sample's physical properties were measured in the field using portable meters (electrical conductivity, pH, temperature and oxidation-reduction potential) at the time of sampling. Samples were placed in clean containers provided by the analytical laboratory (glass for organics, acid-washed polyethylene for heavy metals and other inorganics) and immediately placed on ice. Nitric acid was used to preserve samples for metals analysis, and cadmium nitrate and sodium hydroxide were used to preserve samples for cyanide analysis.

Sampling trips were planned to last only two to three days to minimize holding times. The chilled samples brought from the field were transferred at the office to lightweight coolers packed with insulating material and gel 'freezer packs' and shipped to the analytical laboratory via international courier,

Table 1 | Summary of water sources sampled

Source type	No. samples	Comments
Urban water supply – ground water source	7	Mostly untreated ground water
Urban water supply – surface water source	8	Most treated to reduce turbidity, but not chlorinated
Rural drilled wells	64	Includes three 'combination' drilled/dug wells
Rural 'open' wells	9	Shallow hand-dug wells, usually <10 m deep
Surface water bodies	6	Mekong, Tonle Sap, Prek Thnaot, and Stueng Saen rivers and one local pond
Subtotal – main round samples	**94**	
Follow-up samples	21	Collected in areas of high arsenic identified during main round
Total samples	**115**	

generally within one to three days of sampling. Courier shipments generally arrived at the laboratory within two to three days after leaving Cambodia, meaning sample holding times were typically one week or less, and therefore within acceptable limits for most parameters. However, holding times for nitrate and nitrite were generally exceeded, as the recommended limits for unpreserved, chilled samples are typically 24 to 48 hours (*Standard Methods* 1998). Due to possible degradation of the samples, results reported for nitrate and nitrite may underestimate the actual amount present at the time of sampling. Cyanide also is reactive and unstable, and though the samples were preserved and chilled prior to analysis, it is possible some degradation did occur during storage.

In addition, the carbonate and bicarbonate results need to be treated with some caution. While those tests were performed on samples that were not acidified, and efforts were made to minimize headspace in the sample containers, there may have been some interchange between headspace CO_2 and dissolved carbonate species.

Analytical parameters and methods

Samples were analysed for 15 trace metals, two classes of organic pesticides, cyanide and an additional 15 inorganic parameters. A summary of the parameters tested and the laboratory methodology is provided in Table 2.

The chemical parameters were selected based on their significance to human health or to the aesthetic properties of the water. Organochlorine and organophosphate pesticides were selected for analysis based on available reports, which indicated that many of the commonly used pesticides in Cambodia fell into these categories (Specht 1996).

Analytical work was performed in Australia by the Queensland Natural Resources Sciences Laboratory, in conjunction with the Commonwealth Scientific and Industrial Research Organisation and the Animal Research Institute. All facilities were accredited by the Australian National Association of Testing Authorities for the analyses performed.

Due to the limited total number of samples collected for the assessment, only ten samples were used for quality assurance and control. Of these, six were 'blind' duplicates used to check the precision of the laboratory tests; two were follow-up retests to confirm high levels of arsenic observed during the main round of sampling; and two were 'trip blanks' used to check whether sample storage containers, ground transport, or air shipping environments had any impact on test results. 'Spiked' samples (samples inoculated with known concentrations of specific parameters) were not used, due to the difficulty of obtaining technical grade reagents in Cambodia.

Blind duplicate analyses indicated that the analytical results generally fell within the laboratory's precision limits.

Table 2 | Parameters tested and analytical methods

Parameters	Instrumentation
Trace metals (Al, Sb, As, Ba, Be, Cd, Cu, Fe, Pb, Mn, Hg, Mo, Ni, Se, Zn)	Inductively coupled plasma/mass spectrometer
Organochlorine and organophosphate pesticides (46 individual compounds)	Gas chromatograph; gas chromatograph/mass spectrometer
Cyanide	Spectrophotometer
Carbonate and Bicarbonate	Titration
Hardness	Calculation
Metals (Ca, K, Mg, Na, B)	Inductively coupled plasma/atomic emission spectrometer
Ammonia	Segmented flow analyser
Nitrate/Nitrite, Cl^-, F^-, SO_4^-	Ion chromatograph
Sodium adsorption ratio	Calculation
Total dissolved ions	Calculation

There were several cases where duplicate sample results differed by more than the precision limits; however, in most of these instances the parameters in question were at relatively low concentrations (close to the detection limit). In other cases, the differences could be accounted for by variations attributable to the field collection method. Moreover, the parameters in question were generally of no health significance (e.g. calcium, zinc). Blind duplicate test results for arsenic were all within laboratory precision limits, and follow-up retests of sources with elevated arsenic showed very close correlation with the results from the main round of sampling.

Trip blanks showed no detectable contamination, indicating that there was no significant influence on the test results from the sample containers, sample preservatives, or from the sample storage or transport environments. The overall results of the quality assurance sampling indicate that the laboratory results were sufficiently accurate for the purposes of this assessment, that is, for characterizing the general chemical quality of the sampled drinking water, and for identifying chemicals of health or aesthetic water quality concern.

RESULTS

A summary of the analytical testing results is provided in Table 3. Results showed that approximately one-third of the water sources tested exceeded WHO's Guideline Values for parameters of health concern, and nearly 46% exceeded Cambodia's recently promulgated Drinking Water Quality Standards (CDWQS). Most of the exceedences of the CDWQS were related to high manganese and iron levels (note that the CDWQS do not differentiate between parameters of health and aesthetic concern). Apart from iron and manganese (and other parameters of aesthetic concern), most samples contained relatively low levels of total dissolved solids and had acceptably low concentrations of heavy metals and other potentially toxic chemicals. Concentrations of the 46 different pesticides tested (chiefly organochlorine and organophosphate compounds) were below detection levels in all 94 'main round' samples. The major surface water bodies sampled during the assessment, including the Mekong and Tonle Sap rivers, also had low levels of dissolved solids and no detectable pesticides.

Arsenic in ground water

Arsenic was found in ground water used for both urban and rural water supplies. Arsenic concentrations during the main round of sampling ranged as high as $326\,\mu g\,l^{-1}$. Eight samples (8.5% of the total) exceeded the WHO arsenic guideline value of $10\,\mu g\,l^{-1}$, and three samples (3.2%) exceeded the recently adopted CDWQS for arsenic of $50\,\mu g\,l^{-1}$.

The elevated arsenic concentrations were observed in wells located near major watercourses such as the Mekong River and its tributaries and distributaries, and in areas where the surficial geology comprised sediments of Quaternary age. Areas along the Mekong and Bassac rivers to the south and southeast of Phnom Penh (in neighbouring Kandal Province) appeared to have the highest concentrations in the study area. Figure 2 shows the arsenic-affected sampling locations.

Owing to the potential health significance of elevated levels of arsenic in drinking water, follow-up sampling was conducted in the portion of the study area that appeared to have the highest arsenic concentrations – Kien Svay and Takhmau districts of Kandal Province. Of the 16 follow-up samples taken from these two districts, 11 (nearly 70%) exceeded $10\,\mu g\,l^{-1}$, and ten exceeded $50\,\mu g\,l^{-1}$. Concentrations ranged up to $504\,\mu g\,l^{-1}$ and averaged over $130\,\mu g\,l^{-1}$, confirming that ground water in this densely populated area lying between the Mekong and Tonle Bassac rivers is highly affected by arsenic. Of the two districts re-sampled, Kien Svay appeared to have the higher concentrations as well as a higher percentage of affected wells (80% exceeded $50\,\mu g\,l^{-1}$).

Table 4 provides a summary of all arsenic-affected wells sampled during the assessment. The household and community wells with elevated arsenic had all been installed within the past 10 years, though a few of the urban supply wells were considerably older. The average depth of arsenic-affected household and community wells was approximately 40 metres, while the urban supply wells ranged from 52 to 209 metres in depth.

Most of the arsenic-affected wells also had high levels of iron and manganese, in addition to low oxidation–reduction potential (Eh). This is consistent with the occurrence of arsenic in other parts of Asia (e.g. Bangladesh,

Table 3 | Summary of analyses from main round of sampling

Parameter	No. samples	Conc. Units	Limit of quantitation	Min. observed	Max. observed	Mean	WHO guideline value	No. of times exceeded	Cambodia DWQS	No. of times exceeded
Aluminium	94	$\mu g\,l^{-1}$	10	<10	780	75.2	100	15	–	–
Alkalinity	94	$mg\,l^{-1}$	0.1	<0.1	798	211	–	–	–	–
Ammonia	94	$mg\,l^{-1}$	0.1	<0.1	12.1	0.41	1.5	5	–	–
Antimony	94	$\mu g\,l^{-1}$	0.2	<0.2	1.5	0.22	**20**	0	–	–
Arsenic	94	$\mu g\,l^{-1}$	0.5	<0.5	326	8.90	**10**	8	50	3
Barium	94	$\mu g\,l^{-1}$	1	<1	676	106	**700**	0	1,000	0
Beryllium	94	$\mu g\,l^{-1}$	1	<1	1	<1	–	–	–	–
Boron	94	$\mu g\,l^{-1}$	300	<300	300	<300	**500**	0	–	–
Bromide	93	$\mu g\,l^{-1}$	10	20	2,800	270	–	–	–	–
Cadmium	94	$\mu g\,l^{-1}$	0.05	<0.05	0.68	0.07	**3**	0	10	0
Calcium	94	$mg\,l^{-1}$	0.07	0.09	279	40.8	–	–	200	1
CO_3	94	$mg\,l^{-1}$	0.1	<0.1	2.9	0.13	–	–	–	–
HCO_3	93	$mg\,l^{-1}$	0.1	3.5	974	259	–	–	–	–
Chloride	94	$mg\,l^{-1}$	0.1	1.1	1,060	56.0	250	5	300	3
Chromium	94	$\mu g\,l^{-1}$	0.5	<0.5	237	4.1	**50**	1	50	1
Conduct. (Field)	94	$\mu S\,cm^{-1}$	1	22	5,900	634	–	–	–	–
Conduct. (Lab)	94	$\mu S\,cm^{-1}$	1	10	3,680	592	–	–	–	–
Copper	94	$\mu g\,l^{-1}$	0.5	<0.5	6.7	1.3	2,000	0	1,500	–
Cyanide	94	$\mu g\,l^{-1}$	10	<10	30	10	**7**	0	20	2
Eh	21	mV	–	-450	406	82.0	–	–	–	–
Fluoride	94	$mg\,l^{-1}$	0.01	<0.01	2.9	0.44	**1.5**	2	1	4
Hardness	94	$mg\,l^{-1}$	0.1	0.43	902	164.9	–	–	300	16
Iron	94	$\mu g\,l^{-1}$	10	12	13,600	1,392	300	59	1,000	30
Lead	94	$\mu g\,l^{-1}$	0.05	<0.05	16.2	0.64	**10**	1	10	1
Magnesium	94	$mg\,l^{-1}$	0.07	<0.07	97	15.3	–	–	150	–
Manganese	94	$\mu g\,l^{-1}$	1	<1	4,080	290.4	**400**/100	**21**/41	500	16
Mercury	94	$\mu g\,l^{-1}$	0.05	<0.05	0.62	0.18	**1**	0	1	0
Molybdenum	94	$\mu g\,l^{-1}$	0.5	<0.5	70.8	1.41	**70**	1	–	–
Nickel	94	$\mu g\,l^{-1}$	1	<1	17.9	2.48	**20**	0	–	–
Nitrate	94	$mg\,l^{-1}$	0.1	<0.1	447	9.02	**50**	3	45	3
Nitrite	57	$mg\,l^{-1}$	0.1	<0.01	13.5	0.39	**3**	1	–	–
pH Field	94	pH units	–	4.27	8.1	6.66	–	–	6.5–8.5	26

Table 3 | (*continued*)

Parameter	No. samples	Conc. Units	Limit of quantitation	Min. observed	Max. observed	Mean	WHO guideline value	No. of times exceeded	Cambodia DWQS	No. of times exceeded
pH Lab	94	pH units	–	4.4	8.2	6.95	–	–	–	–
Potassium	94	$\mathrm{mg\,l^{-1}}$	0.07	<0.07	143	4.83	–	–	–	–
Sodium	94	$\mathrm{mg\,l^{-1}}$	0.1	0.78	623	64.9	200	6	–	–
Selenium	94	$\mathrm{\mu g\,l^{-1}}$	1	<1	35.4	2.02	**10**	2	10	2
Sulphate	94	$\mathrm{mg\,l^{-1}}$	0.1	<0.1	177	12.7	250	0	250	0
Total dissolved ions	94	$\mathrm{mg\,l^{-1}}$	1	16.7	2,340	463	1,000	6	1,500	3
Temp. (°C)	94	Deg. C	–	27.9	32	29.6	–	–	–	–
Zinc	94	$\mathrm{\mu g\,l^{-1}}$	1	2.1	9,580	140	4,000	1	1,500	1
OC Pesticides	94							0		0
OP Pesticides	94							0		0

Notes: WHO guideline values for parameters of health concern are noted in bold typeface. There were no cases of pH exceeding 8.5; the lowest recorded pH was 4.27.

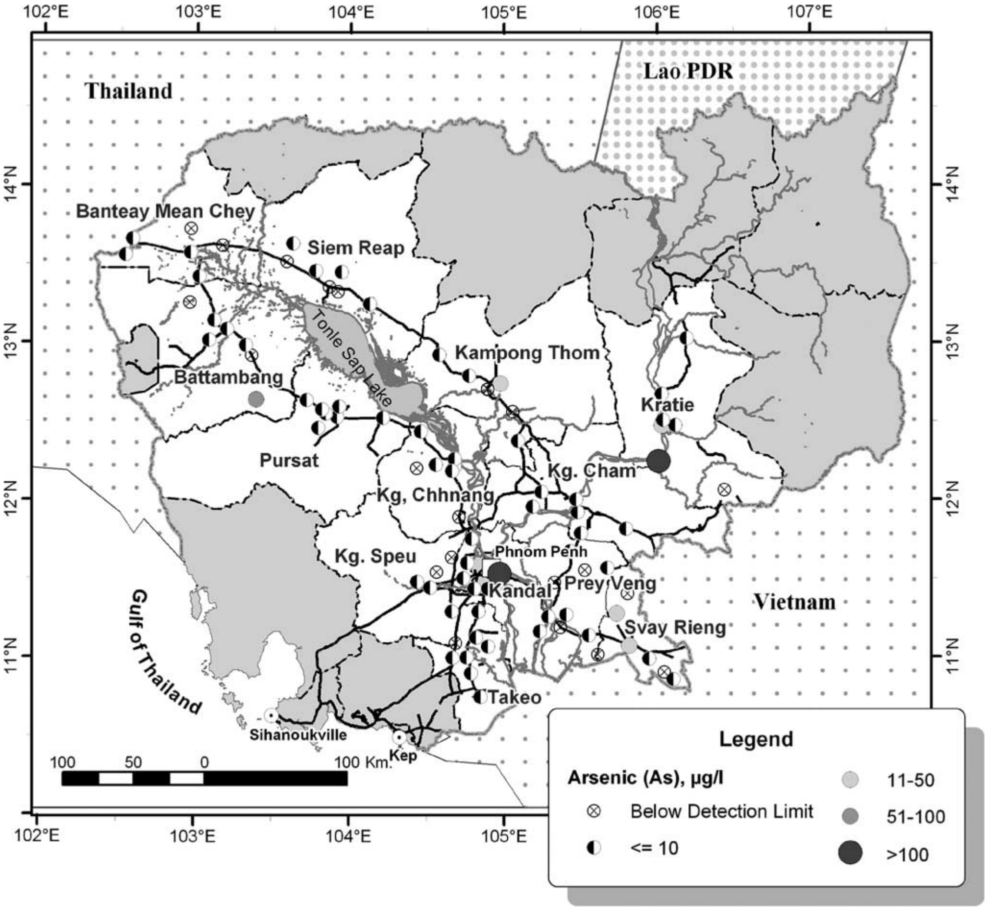

Figure 2 | Arsenic concentrations.

India and Vietnam) where high arsenic concentrations also occur in alluvial and deltaic sediments of Quaternary age (Nickson *et al.* 2000; Smedley 2003). Arsenic release is likely to be related to the strongly reducing conditions in these aquifers, conditions that lead to the reductive dissolution of the abundant iron oxides in the sediment, along with trace metals such as arsenic and manganese which are associated with the iron (DPHE/BGS/MML 1999). The reducing conditions are believed to result from decomposition of organic material in the sediments, compounded by low ground water flow velocities (another common characteristic of arsenic-affected areas in the region).

Though reducing conditions and high iron and manganese levels are often found in areas with high arsenic concentrations, statistical correlations between arsenic and these other parameters tend to be of only moderate strength. Data from this assessment indicated that the correlation between arsenic and iron was significant (Kendall's tau (τ_b) = 0.37) as was the (negative) correlation between arsenic and Eh ($\tau_b = -0.42$). Though these

Table 4 | Water sources with elevated arsenic levels

Sample no.	Province/district	Source type	Depth (m)	Arsenic ($\mu g\,l^{-1}$)	Eh (mV)	Iron ($\mu g\,l^{-1}$)	Mn ($\mu g\,l^{-1}$)	pH	Year installed
BBG-2	Batdambang/Moung Russei	Community well	29	69.0	93	12,600	532	6.55	1998
KAN-1	Kandal/Kien Svay	Urban supply well	65	32.5	–	279	947	7.26	Unknown
KAN-3	Kandal/Kien Svay	Household well	60	326	–	8,840	142	7.03	1999
KAN-9*	Kandal/Kien Svay	Household well	40	84.4	−143	239	81.3	7.00	1999
KAN-16*	Kandal/Takhmau	Urban supply well	52	85.8	−234	999	982	7.44	1996
KAN-19*	Kandal/Takhmau	Household well	33	71.9	−364	6,510	500	6.89	1997
KAN-21*	Kandal/Kien Svay	Household well	53	504	−389	6,290	1,590	7.18	1997
KAN-22*	Kandal/Kien Svay	Household well	24	89.7	−315	13,700	376	6.70	1996
KAN-23*	Kandal/Kien Svay	Household well	40	120	−335	9,250	379	6.82	1999
KAN-24*	Kandal/Kien Svay	Household well	48	338	−340	1,010	179	7.80	2000
KAN-25*	Kandal/Kien Svay	Household well	54	28.0	−282	460	410	7.25	1998
KAN-27*	Kandal/Kien Svay	Household well	57	438	−370	4,880	559	7.34	Unknown
KAN-28*	Kandal/Kien Svay	Household well	40	189	−347	14,000	185	6.87	1996
KAN-29*	Kandal/Kien Svay	Household well	53	196	−333	9,090	88.8	6.84	1997
KRT-2	Kratie/Kratie	Urban supply well	209	43.8	−270	1,120	166	7.22	1962
KRT-8	Kratie/Chhlong	Community well	37	119	−450	13,600	135	6.73	1999
KTH-3	Kampong Thom/Kampong Svay	Community well	22	27.2	–	10,800	771	6.51	1998
SVR-1	Svay Rieng/Svay Rieng	Urban supply well	120	13.8	–	3,880	231	6.50	1952
SVR-5	Svay Rieng/Romeas Haek	Community well	42	36.3	–	3,210	297	6.87	1994

*denotes follow-up samples in Kandal Province.

correlations are statistically significant, they are of limited practical use for predicting the occurrence of arsenic, a conclusion reinforced by the examination of scatter-plots of the data. Low iron concentrations and high Eh probably indicate low potential for elevated arsenic in Cambodia, though firm conclusions about such relationships should not be drawn until aquifer conditions throughout the country have been better characterized.

Other parameters of potential health concern

In addition to arsenic, ten other parameters of potential health concern were exceeded in one or more samples throughout the study area:

Manganese

The CDWQS of 500 $\mu g\,l^{-1}$ was exceeded 16 times during the main round of sampling, or in 17% of cases (WHO's health-based GV of 400 $\mu g\,l^{-1}$ was exceeded 21 times). The highest observed level was 4,080 $\mu g\,l^{-1}$.

Nitrate and nitrite

Four samples exceeded the CDWQS of 45 $mg\,l^{-1}$ for nitrate, and one sample exceeded the WHO guideline value of 3 $mg\,l^{-1}$ for nitrite. All four samples were from different provinces. One sample from Siem Reap Province exceeded the recommended limit for nitrate almost by a factor of ten (447 $mg\,l^{-1}$). Though water from this well also had very high levels of dissolved solids and hardness, residents reported they used it for drinking. (Note that nitrite analyses were conducted in only 8 of 13 provinces studied, and that recommended holding times for all nitrate and nitrate were exceeded; observed levels may be artificially low as a result).

Fluoride

The CDWQS of 1.0 $mg\,l^{-1}$ was exceeded at four locations during the assessment; the highest level observed was 2.9 $mg\,l^{-1}$. Elevated fluoride levels were also detected in Cambodia during field tests conducted in the mid-1990s (SAWA 1998). At that time, levels between 1 and 3 $mg\,l^{-1}$ were found in 18% of wells tested in five central and southeastern provinces (Kampong Cham, Kampong Chhnang, Kampong Speu, Takeo and Svay Rieng provinces).

Barium

There were no exceedences of the CDWQS of 1,000 $\mu g\,l^{-1}$ for barium during the main round of sampling; however, two of the follow-up samples in Kandal Province exceeded this limit. The affected sources were both private household wells; the highest barium concentration observed (1,820 $\mu g\,l^{-1}$) was from the location where the highest arsenic concentration was observed. A public water supply well in Kandal's provincial capital had a barium concentration of 776 $\mu g\,l^{-1}$, which is in excess of the WHO guideline value of 700 $\mu g\,l^{-1}$.

Cyanide

The CDWQS of 0.02 $mg\,l^{-1}$ was slightly exceeded in two samples (0.03 $mg\,l^{-1}$), while the limit of quantitation was 0.01 $mg\,l^{-1}$ (the WHO guideline value for cyanide is 0.07 $mg\,l^{-1}$). All other samples were below the detection limit. (As mentioned previously, because of the reactivity of cyanide, some losses may have occurred during storage of the samples.)

Lead

The WHO GV of 10 $\mu g\,l^{-1}$ for lead was exceeded in one urban water sample from Prey Veng Province (16.2 $\mu g\,l^{-1}$). This sample also had a high concentration of zinc, suggesting that pump or pipe corrosion may in part be responsible.

Other parameters

Elevated levels of selenium, molybdenum and chromium were also observed in a limited number of cases. A single sample from Batdambang Province (237 $\mu g\,l^{-1}$) exceeded the CDWQS chromium limit of 50 $\mu g\,l^{-1}$. Two samples (from Takeo and Kandal provinces) exceeded the CDWQS selenium limit of 10 $\mu g\,l^{-1}$. A single sample slightly exceeded the WHO GV of 70 $\mu g\,l^{-1}$ for molybdenum (no CDWQS exists).

Parameters of aesthetic concern

The most common dissolved minerals affecting the aesthetic properties of ground water were iron, manganese, sodium chloride and hardness (calcium and magnesium). Of these, iron and manganese were the most common, and were often at levels far above the recommended aesthetic limit. Iron ranged as high as $14\,\mathrm{mg\,l^{-1}}$, and nearly one-third of all samples exceeded the CDWQS of $1.0\,\mathrm{mg\,l^{-1}}$ (the WHO recommended aesthetic limit is $0.3\,\mathrm{mg\,l^{-1}}$, which was exceeded in over 60% of the samples). Manganese exceeded the WHO recommended aesthetic limit of $0.1\,\mathrm{mg\,l^{-1}}$ in 43% of the samples.

Chloride levels exceeded the CDWQS of $300\,\mathrm{mg\,l^{-1}}$ in only three cases (WHO's recommended limit of $250\,\mathrm{mg\,l^{-1}}$ was exceeded five times).

Hardness levels were 'high' at 16 locations according to the CDWQS (in excess of $300\,\mathrm{mg\,l^{-1}}$). High hardness levels were cited as leading to scale deposits in cooking pots, and also appeared to be related to complaints of bitter-tasting water.

DISCUSSION

Arsenic

The key finding of the assessment was the confirmation of elevated levels of dissolved arsenic in both urban and rural water supply sources in Cambodia. While a larger number of samples exceeded the CDWQS for manganese than for arsenic, the authors and government agencies involved in the study note the documented links between arsenic-affected drinking water and moderate to severe human health impacts elsewhere in Asia as well as other parts of the world. As the human health threat from elevated levels of manganese is less well documented and apparently less severe, it was concluded that arsenic represented the most significant public health threat identified in this assessment.

Inorganic arsenic can be both carcinogenic and toxic when consumed at low doses over long periods of time, resulting in chronic arsenic poisoning or 'arsenicosis'. A wide variety of adverse health outcomes have been attributed to arsenic exposure, including non-cancer effects such as skin disorders (keratosis, melanosis and depigmentation), numbness, dizziness, palpitations, fatigue, sleep disorders, anorexia and abdominal pain (IARC 1987; Lianfang & Shenling 2003). A large number of health impact studies of arsenic are reviewed in Abernathy *et al.* (1997) and WHO (2001). Many of these studies have confirmed the link between long-term arsenic exposure and vascular disease. Other long-term effects often attributed to arsenic intake, such as diabetes, hypertension, respiratory problems and stillbirth show varied results in those studies. Some health outcomes are demonstrated in one country but not another (raising the question of confounding variables), while others show weak or inconclusive evidence. As a carcinogen, arsenic is linked to increased risk of skin, lung, bladder and kidney cancers. In children exposed to arsenic, cognitive development and intellectual functions may be weakened, although the evidence for this is inconclusive (Wasserman *et al.* 2004).

There is no known effective medical treatment for arsenicosis; however, exposure to the source should be stopped as soon as possible to help prevent or arrest the development of adverse effects. As the latency period for the onset of detectable symptoms can exceed 10 years, switching to an arsenic-safe water supply is highly advisable as soon as practicable, even if symptoms of arsenicosis have not yet been detected in the exposed population.

Identification of naturally occurring arsenic in Cambodian ground waters during this assessment prompted the Ministry of Rural Development, the Ministry of Industry, Mines, and Energy, UNICEF and other development agencies to conduct tests for arsenic in many portions of the country, both within and outside of this assessment's study area. To date, over 10,000 individual wells have been tested, mostly using portable semi-quantitative field kits.

Data from these more recent tests suggest that the areas of greatest arsenic contamination risk are in the vicinity of major surface watercourses and/or areas underlain by Quaternary-age sediments. Figure 3 shows a recently compiled map of arsenic risk in Cambodia, prepared by the Ministry of Rural Development and UNICEF. In this figure, the 'medium' and 'high' risk areas correspond to areas underlain by Pleistocene and Holocene-age sediments, respectively (Fredericks 2004). These risk areas were identified based on actual well-testing results and by inference from detailed arsenic mapping in other countries in the region (where highest arsenic risk has been shown to occur in deltaic and flood-prone sedimentary units). It is significant that the recently updated arsenic risk areas in Cambodia are generally consistent with those identified or predicted from the 2001 assessment.

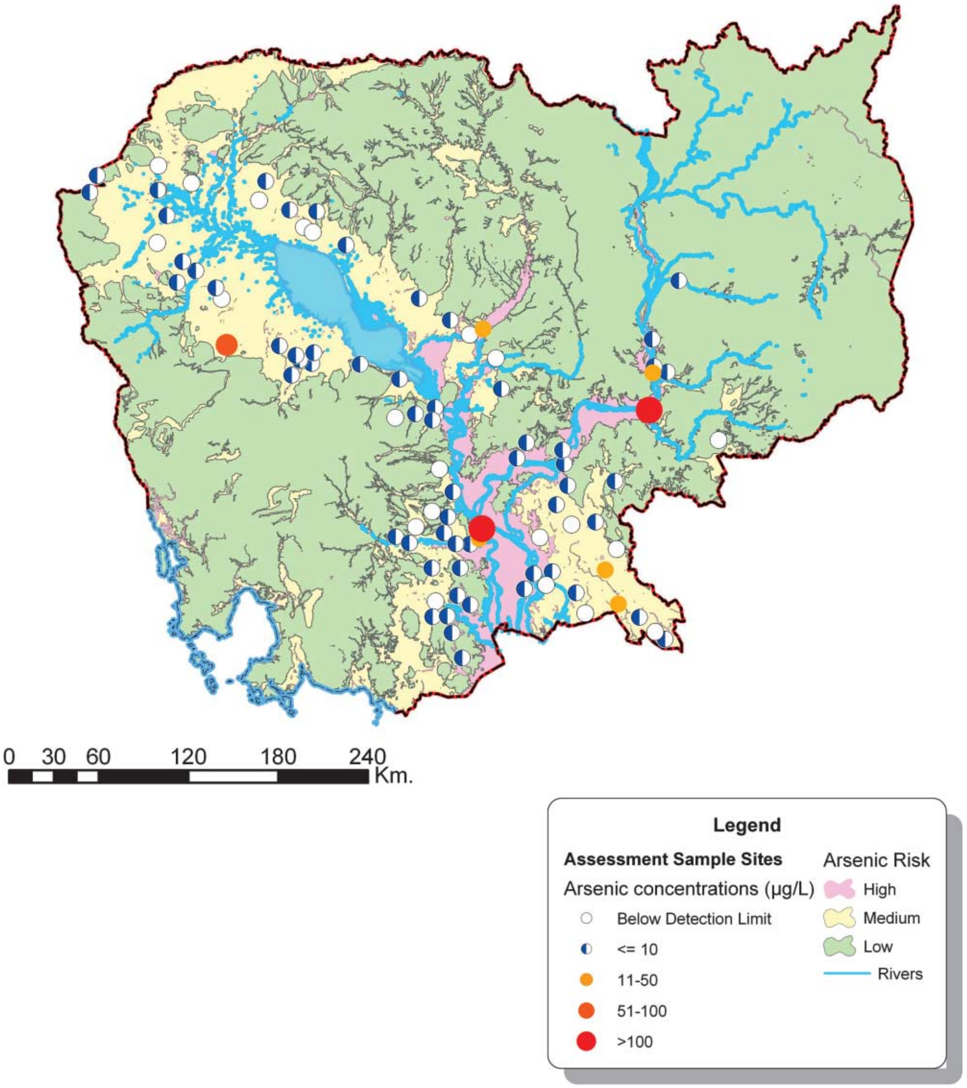

Figure 3 | Arsenic risk map of Cambodia.

Nationally, about 15% of the wells tested to date exceed the CDWQS of 50 $\mu g\, l^{-1}$; however, it should be noted that field testing for arsenic has been targeted mainly within suspected moderate to high risk areas. Therefore, the figure of 15% may overestimate the situation nationally. In the high-risk areas in Kandal Province (located in the lower central portion of Figure 3), 46% of the wells tested have exceeded the 50 $\mu g\, l^{-1}$ limit (Fredericks 2004).

Most of the wells located in the highly arsenic-affected areas are still relatively new (and, hence, human exposure periods are still relatively short). However, in some of these areas the local conditions (soft soils and a shallow ground water table) have encouraged the proliferation of low-cost private wells, resulting in rapid expansion of the at-risk population. Arsenic testing, education and mitigation programmes should therefore be undertaken expeditiously and address both public and private water supply sources in these areas. Agencies involved in the development of new drinking water supplies should carefully evaluate local water quality conditions, and in particular arsenic concentrations, before exploiting ground water in areas considered to be of moderate to high risk.

Arsenic mitigation efforts are in the pilot stage and will require additional time to be refined and scaled up.

Fortunately, alternative water sources in arsenic-affected areas are often readily available, including surface water and rainwater. Observations made during the assessment indicated that consumers in many arsenic-affected areas preferred using rain and/or surface water for drinking, owing to the presence of high concentrations of iron, manganese or other elements in the ground water. However, attitudes concerning palatability may change over time if consumers continue to use ground water regularly and become more accustomed its taste. Further, the high levels of microbiological contamination common in surface waters, and the prolonged dry season in Cambodia mean that the cost and technical practicability of using surface and/or rainwater as alternative drinking water sources must be carefully evaluated to ensure that they are capable of providing an adequate quantity and quality of drinking water year-round.

Other potential health concerns

Elevated concentrations of other parameters of public health concern warrant further attention and study in Cambodia. Based on the results of this assessment, the parameters most likely to be of greatest concern include nitrate and nitrite, fluoride, manganese and barium.

Elevated nitrate and nitrite were identified in a small number of samples and there was no apparent pattern in their occurrence. Nitrates and nitrites have known human health impacts, primarily in infants (who are typically exposed through baby formula made with the affected water source). Breastfed infants do not appear to be at risk. Nitrate and nitrite affect haemoglobin in the blood and reduce the baby's ability to transport oxygen; infants so affected are said to have 'blue baby syndrome'. There is also a suspected link between exposure to nitrates and nitrites and cancer in humans (WHO 2004*b*). As the most common origins of nitrates and nitrites in ground water are agricultural activity and disposal of untreated human waste (both of which are very common in Cambodia), nitrate and nitrite should be considered a high priority for future water quality surveillance.

Fluoride ingestion has known effects on human teeth and the skeletal system. A significant portion of human fluoride exposure is typically through dietary sources, as well as from drinking water. Low levels of fluoride intake are associated with enhanced resistance to tooth decay; many municipal water systems add small amounts of fluoride to their treated water as a preventive dental health measure (concentrations are typically between 0.5 and 1.0 $\mathrm{mg\,l^{-1}}$). However, at higher concentrations and with long-term exposures, fluoride may lead to mottling and discoloration of teeth during their developmental stage, and to skeletal problems (known as skeletal fluorosis) (WHO 2004*b*). No evidence of fluoride-related health effects has been put forward in Cambodia, though detailed studies have not yet been performed. Fluoride levels exceeding the CDWQS in this and other water quality assessments in Cambodia suggest that fluoride should be considered of moderate to high importance in future surveillance programmes.

Manganese exceeded the recommended CDWQS in nearly one-fifth of the water sources sampled; its pattern of occurrence was similar to that of iron. Manganese is an essential human micronutrient and most human intake occurs through consumption of various types of food. Data on the human health effects of long-term exposure to elevated manganese levels through oral intake are limited; however, inhalation studies link chronic manganese intake with neurological disorders (ATSDR 2000; WHO 2004*b*). Manganese should be considered of moderate importance for future water quality surveillance and mitigation efforts.

Two water sources exceeded the CDWQS of 1,000 $\mu\mathrm{g\,l^{-1}}$ for barium during the follow-up sampling for arsenic in Kandal Province, and a third exceeded the WHO guideline value of 700 $\mu\mathrm{g\,l^{-1}}$. Barium's main long-term human health effect at the chronic dose level appears to be hypertension; there are no data suggesting a link to cancer or other significant health endpoints (WHO 2004b). Barium can probably be considered of low importance in future water quality surveillance.

Other parameters that exceeded CDWQS or WHO guideline values in one or a small number of samples during this assessment (such as cyanide, selenium, molybdenum, lead and chromium) are not likely to represent significant health concerns, though they should not be completely overlooked. Concentrations of those samples that did exceed recommended limits did so by a relatively small margin. However, the elevated lead level observed in an urban water supply system could indicate a potential problem with older pipes and fittings (this sample also had elevated zinc). Lead and zinc levels should probably be considered of importance when conducting surveillance of water treatment plants and distribution networks.

Aesthetic properties

Consumers in rural areas typically prefer rainwater, surface water or ground water from very shallow (typically less than 8 metre-deep) hand-dug wells, as opposed to ground water from deeper 'hand-pump' wells. This is especially true where deeper aquifers contain dissolved minerals which impart noticeable taste or other properties that are deemed objectionable (e.g. discoloration of food, staining of laundry, precipitation of solids in cookware). This consumer concern with the aesthetic properties of water is often ignored or underestimated by agencies involved in rural water supply projects, which tend to focus exclusively on improving the microbiological quality of water sources.

Observations made during the assessment indicate that a significant number of wells in rural Cambodia are no longer used for drinking water purposes (or are completely non-functional because of pump breakdowns). Some of these wells were less than 2 years old at the time the assessment was conducted. Local residents indicated that the main reason the wells were not in use or were in disrepair was that the aesthetic properties of the water had been unacceptable to the community. These concerns were typically related to high iron (or manganese) levels, and in some cases elevated hardness. Sodium chloride levels were elevated in a very small number of samples and did not appear to be a widespread concern.

Residents in rural areas using well water containing high iron levels often allow the water to aerate and settle for up to several days before drinking it in order to improve the water's taste. Though moderately effective, this household treatment approach can increase opportunities for bacterial contamination if not done in a clean, limited-access vessel. Some wells were observed to have simple iron reduction filters attached. If properly maintained, such filters can significantly reduce iron (and manganese) concentrations and improve taste, although ensuring that regular cleaning, replacement of filter media and sterilization processes are undertaken can prove problematic at community-owned wells. Use of iron reduction filters can also lower elevated arsenic levels through the co-precipitation of arsenic with the iron, though this approach does not reliably reduce arsenic concentrations to levels in compliance with drinking water standards (Ahmed 2001). Importantly, where other sources of water were available, residents in these areas tended to use well water for drinking only when absolutely necessary (such as during the extended dry season).

Apart from the usual considerations with elevated levels of hardness (such as scaling and taste), some rural consumers expressed concern with what they considered to be a link between high water hardness and the risk of kidney stones in their families or communities. However, these concerns were not always aired at locations where the hardness levels actually were elevated, suggesting that these concerns stemmed from other factors or beliefs. Concerns with the link between water hardness and kidney stones have been raised in many parts of the world, but such linkage is considered unlikely (Schwartz *et al.* 2002). As insufficient hydration is often a contributing factor in the formation of kidney stones, a high fluid intake (regardless of water hardness) is generally recommended as a preventive measure (Jaeger *et al.* 1984).

Concerns with the aesthetic properties of drinking water in urban areas were expressed by a number of those interviewed during the assessment. According to several water treatment plant operators, consumers had objected to the taste and odour imparted by water treatment processes. Three of the 16 urban water systems visited during the assessment had discontinued the use of chlorine dosing equipment, in part due to consumer complaints (other reasons included equipment breakdowns and a lack of supplies). At the time of the study, five of the seven urban systems using ground water wells as sources were delivering the water untreated into the distribution system.

Rapid screening methodology

The Cambodia Drinking Water Quality Assessment was conducted over a period of 12 months for approximately US$75,000. The fieldwork was carried out by two central government technical staff working with a full-time technical adviser (whose salary is included in this budget figure). Fieldwork required the use of one vehicle over a period of 12 weeks. Additional field support was provided by government staff from each province who were temporarily seconded to the team for one to two days to help select and find sampling locations. Additional technical and management support were provided by a part-time technical adviser (also included in the budget figure above) and WHO-Cambodia's environmental engineer.

Approximately 30% of the assessment's budget was allocated to the laboratory analysis and express shipment of samples. Supplies and equipment purchase represented less than 5% of the total cost. Staff, transport and technical advisory support made up the balance of expenditures.

The small amount of resources needed to conduct this assessment makes it a potentially viable approach for agencies working in other developing countries. By using a low sample density and rapid screening approach, Cambodia's leading government water supply agencies were able to identify key chemical parameters of health and aesthetic concern. Early identification of these parameters, and of arsenic in particular, is having a significant and beneficial impact on the development of drinking water supplies in the country. Water quality testing conducted subsequent to this assessment (particularly arsenic testing) has confirmed that the major findings of this assessment were relevant and sufficiently accurate to provide the basis for further action. Results of the assessment have also helped as an incentive and guide for the development of national drinking water quality standards, as well as for other institutional responses such as the creation of an interagency government committee to address the arsenic problem.

CONCLUSIONS

This assessment demonstrated that, within the study area, Cambodia's drinking water sources have reasonably good chemical quality, with key exceptions related to the occurrence of natural arsenic contamination as well as a few other parameters of health significance. While bacteriological contamination of drinking water remains the primary water quality concern in Cambodia from a health perspective, these newly identified chemical water quality concerns are significant and should be addressed.

Arsenic contamination is a public health concern that deserves further attention and immediate action. Characterization and mitigation of the arsenic problem at an early stage of Cambodia's water resource development efforts can help prevent widespread, long-term exposure. Action must therefore be taken before a significant portion of the population in 'high-risk' areas becomes reliant on ground water and therefore vulnerable to arsenic's long-term toxicological effects.

Based on data gathered during and subsequent to this assessment, the highest risk of arsenic occurrence appears to be near major drainages and/or in areas where the surficial geology is dominated by Holocene age sediments. Areas of Pleistocene surficial geology appear to be at moderate risk. These areas should be considered of highest priority for further investigation and mitigation efforts.

Chemicals of health significance other than arsenic (including barium, fluoride, lead, manganese, nitrate and nitrite) should receive further attention and study. Nitrate, nitrite, fluoride and manganese are likely to be the most significant of these and should receive high priority in any future chemical water quality surveillance programmes.

The aesthetic properties of water supplies should also be carefully investigated before developing or bringing new water sources on line, particularly for ground water sources. Water supply investigations should be concerned with aesthetic water quality parameters (e.g. chloride, hardness, iron and manganese) in addition to microbiological quality, as consumer acceptance can play a critical role in the long-term sustainability of water supply projects. Given the potentially large investment needed to develop ground water supplies in many parts of Cambodia, it would seem prudent to investigate both the aesthetic as well as the health-related quality of water sources before recommending that communities begin using them.

The recent promulgation of national drinking water quality standards in Cambodia is an encouraging development and their enforcement should be considered a high priority. A national water quality surveillance programme will be needed, along with the institutional capacity building necessary to enable such a programme to be successful. Along these lines, analytical laboratories in Cambodia are still relatively few in number, and as yet there are no facilities capable of carrying out reliable analyses of trace metals and several other key parameters. Establishment of an independent laboratory facility capable of carrying out a broad spectrum of water quality analyses would greatly enhance Cambodia's ability to transform its water quality regulations into useful tools for protecting public health and the integrity of the aquatic environment.

Finally, the water quality of geographic areas not included in this assessment should be investigated (screening for arsenic has already been done in some of these areas). Investigations of the water quality, and the connection between water quality and geology, would be of substantial benefit to water resources programme planners and implementing agencies. The cost of future water quality studies could be kept to a minimum by focusing primarily on those chemical constituents that were found to be of greatest concern during this assessment and other subsequent studies.

ACKNOWLEDGEMENTS

This study was funded by WHO's Western Pacific Regional Office and supported through WHO's Cambodia country office, which provided both technical and logistical assistance. The authors also wish to thank Dr David Fredericks and UNICEF Cambodia for sharing recently compiled information regarding arsenic occurrence in Cambodia.

REFERENCES

Abernathy, C. O., Calderon, R. L. & Chapell, W. R. (eds) 1997 *Arsenic: Exposure and Health Effects*. Chapman & Hall, London.

Ahmed, M. F. 2001 An overview of arsenic removal technologies in Bangladesh and India. In *Proceedings of BUET-UNU International Workshop on Technologies for Arsenic Removal from Drinking Water*, Dhaka, 5–7 May 2001 Bangladesh University of Engineering and Technology and United Nations University, Bangladesh.

ATSDR (Agency for Toxic Substances and Disease Registry) 2000 *Toxicological Profile for Manganese*. US Department of Health and Human Services, Public Health Service, Atlanta, GA, USA, www.atsdr.cdc.gov/toxprofiles/tp151.html.

DPHE/BGS/MML (Bangladesh Department of Public Health Engineering/British Geological Survey/Mott MacDonald Ltd) 1999 *Groundwater Studies for Arsenic Contamination in Bangladesh. Phase 1: Rapid Investigation Phase, Final Report*. DPHE/BGS/MML, Dhaka, Bangladesh.

Fredericks, D. 2004 *Situation Analysis: Arsenic Contamination of Groundwater in Cambodia*. *Report prepared for UNICEF and the Ministry of Rural Development*. UNICEF, Phnom Penh.

IARC 1987 Overall evaluations of carcinogenicity: an updating of IARC Monograph volumes 1–42. *IARC Monogr. Eval. Carcinog. Risks Hum. Suppl.* **7**, 100–106.

Jaeger, P., Portmann, L., Jacquet, A. F. & Burckhardt, P. 1984 Drinking water for stone formers: Is the calcium content relevant? *Eur. Urol.* **10**(1), 53–54.

Lianfang, W. & Shenling, W. 2003 Arsenic in water and its health effects. In *Aquatic Arsenic Toxicology and Treatment* (ed. in T. Murphy & J. Gao). Backhuys, Leiden, The Netherlands.

MEF (Ministry of Economy and Finance) 2004 *Medium-Term Expenditure Framework for Cambodia: 2005-2007*. Ministry of Economy and Finance, Phnom Penh, Cambodia (Draft).

Nickson, R. T., McArthur, J. M., Ravenscroft, P., Burgess, W. G. & Ahmed, K. M. 2000 Mechanism of arsenic release to groundwater, Bangladesh and West Bengal. *Appl. Geochem.* **15**(4), 403–413.

NIS (National Institute of Statistics of Cambodia) 2002 *General Population Census of Cambodia 1998*, 2nd edn. Cambodia Ministry of Planning Phnom Penh, Cambodia.

NIS (National Institute of Statistics of Cambodia) 2003 *Percent of the Population Living Below the Basic Needs Poverty Line*. Cambodia Ministry of Planning Phnom Penh, Cambodia, www.worldbank.org/data/countrydata/aag/khm_aag.pdf.

NIS (National Institute of Statistics of Cambodia) 2004 *Cambodia Inter-Censal Population Survey 2004, General Report*. Cambodia Ministry of Planning Phnom Penh, Cambodia.

SAWA 1998 *Fluoride Related Problems and Defluorination Methods*. *Draft Report*. SAWA Consultants, Phnom Penh, Cambodia.

Schwartz, B. F., Schenkman, N. S., Bruce, J. E., Leslie, S. W. & Stoller, M. 2002 Calcium nephrolithiasis: effect of water hardness on urinary electrolytes. *Urology* **60**(1), 23–27.

Smedley, P. L. 2003 Arsenic in groundwater - south and east Asia. In *Arsenic in Ground Water: Geochemistry and Occurrence* (ed. in A. H. Welch & K. G. Stollenwerk), pp. 179–209. Kluwer, Dordrecht.

Specht, J. 1996 *Pesticides in Cambodia*. *Report prepared for Lutheran World Service*, Phnom Penh, Cambodia.

Standard Methods for the Examination of Water and Wastewater 1998 20th edition. American Public Health Association/ American Water Works Association/Water Environment Federation, Washington, DC.

UNICEF 2004 *Official Summary of the State of the World's Children 2004*. United Nations Children's Fund, New York.

Wasserman, G. A., Liu, X., Parvez, F., Ahsan, H., Factor-Litvak, P., van Geen, A., Slavkovich, V., Lolacono, N. J., Cheng, Z., Hussain, I., Momotaj, H. & Graziano, J. H. 2004 Water arsenic exposure and children's intellectual function in Araihazar, Bangladesh. *Environ. Health Perspect.* **112**(13), 1329–1333.

WHO 2001 *United Nations Synthesis Report on Arsenic in Drinking Water*, (ed. in). WHO, Geneva (in press).

WHO 2004*a* *Country Situation and Trends (Cambodia)*. WHO, Manila, Philippines, www.wpro.who.int/chips/chip02/cam.htm.

WHO 2004*b* Guidelinesfor Drinking Water Quality. 3rd edition. WHO, Geneva.

Available online September 2006