Water Science & Technology—WST | 61.2 | 2010

Characterisation of the water quality from open and rope-pump shallow wells in rural Cambodia

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ABSTRACT

An 8 month investigation into the quality of water from open and rope-pump shallow wells in rural Cambodia was conducted. Wells were analysed for indicators of the health (arsenic, fluoride, manganese, nitrate, total coliforms, *E. coli*, male-specific coliphage) and aesthetic (iron, chloride, conductivity, total dissolved solids, hardnesss, turbidity, pH) quality of the water, and referenced to the Cambodian Drinking Water Standard when available. The shallow aquifer was chemically less of a health risk than the deep aquifer; however, microbial contamination was considerable for both shallow well types with mean *E. coli* loads of 10^3 CFU/100 mL and male-specific coliphage contamination of 10^2 PFU/eluate. Temporal variation in microbial contamination was significant ($p < 0.05$), with overall loads decreasing during the dry season. The aesthetic quality of the water was poor for all samples, but worsened during the dry season. No significant difference was observed in the quality of water from open and rope-pump wells, despite their classification as unimproved and improved respectively by the WHO/UNICEF Joint Monitoring Programme. Contaminants present in both well types may readily be removed by simple water treatment, suggesting that household treatment may be more beneficial to rural Cambodian households than shallow aquifer source improvements.

Key words | Cambodia, dug wells, groundwater, rope-pump wells, source improvement, water quality

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INTRODUCTION

In light of the recent discovery that aquifers greater than 20m deep within the Mekong River basin in Cambodia have naturally elevated levels of arsenic (Berg *et al.* 2007; Buschmann *et al.* 2008; Luu *et al.* 2009), and that prolonged exposure through drinking water can lead to arsenicosis (Gault *et al.* 2008; Mazumder *et al.* 2009), emphasis has been placed on increasing the utilisation of the shallower aquifers as a source for household and drinking water. Local NGOs, with funding from the World Bank, have increased installation of rope-pump wells with the goal of improving access to safe water (World Bank 2006). As a result, rope-pump wells have quickly become the preferred technology to access the shallow aquifer. To date, over 400 rope-pump systems, with cap, apron, and drain, have been installed in the Kandal province of Cambodia alone. This activity is encouraged by international health organizations and the Cambodian government. The WHO/UNICEF Joint Monitoring Programme for Water Supply and Sanitation differentiate between open wells and rope-pump wells by classifying them as unimproved and improved sources respectively. According to WHO/UNICEF improved sources are those that "by nature of their construction or through active intervention, are protected from outside contamination, particularly faecal matter" (WHO 2008). In addition, the Ministry of Rural Development is considering a pump registration process, which would make the rope pump an officially accepted water pump in Cambodia. Previous examination of the

doi: 10.2166/wst.2010.817

impact that rope-pumps may have on water quality has been limited to a randomised control trial by Gorter *et al.* (1995) in Nicaragua. Their study found no reduction in faecal coliform contamination when windlass wells were fitted with rope-pumps, yet a 62% reduction when rope and bucket wells were fitted with rope-pumps. The authors attribute the improvement to the elimination of the rope and bucket as a source of contamination, and not an improvement of the quality of source water.

This study represents a 27-week investigation into shallow well water quality in rural Cambodia. Specifically we aimed to: (1) determine the water quality of the shallow aquifer as accessed by both open and rope-pump wells with respect to potential contaminants of concern, (2) assess the magnitude of temporal variation in water quality, and (3) determine if there was a statistically significant difference between open and rope-pump well water quality.

METHODS

Area of study

The district of Kien Svay (Kandal Province, Cambodia) lies approximately 10 km southeast of Phnom Penh along National Route 1, bordered by the Mekong River to the north, and Bassac River to the southwest. The study presented herein was carried out in the semi-rural communes of Kbal Kaoh (pop. 14,903, 2004) and Preaek Aeng (pop. 12,960). For both communes households are densely located along access roads and surrounded by agricultural lands. Monsoon rains divide the region into two seasons, with the rainy season lasting from May to November with average rainfalls of 175 mm/month. Households in the area utilise water from a variety of sources, including captured rainwater, surface water, shallow dug wells, and tube wells; in addition to limited use of piped water connections or vendors.

Source selection and sampling

In July of 2008, 17 active wells (eight open (O) and nine rope-pump (RP)) were identified in Kbal Kaoh and Preaek Aeng and selected for further study. Household surveys were conducted by a Resource Development International (RDI)–Cambodia field team to determine the socioeconomic status of the home and assess environmental characteristics potentially relevant to water quality. Sampling began in late July and continued through February 2009. During the first 4 weeks water samples were collected for all wells every 7 days (+/− 1). Thereafter, sampling was grouped into odd and even wells, with each group being sampled every 14 days. One litre was collected for microbial analysis, 500 mL for chemical analysis, and 25 mL was collected in an acidified bottle for arsenic analysis. RP wells were pumped for at least 10 seconds such that samples were representative of the standing well water just above the bottom of the well and not water or contamination in the well tubing. Sample collection vessels for O wells were lightly rinsed with well water to remove gross contamination prior to sampling. Samples were collected from drop buckets and are representative of conditions at the surface of the water (as opposed to near the bottom for RP wells). All samples were stored on ice until transported to the laboratory (maximum 2 h), microbial samples were then held at 4°C until analysis (maximum 24 h for initial processing, 48 h if analysis was repeated), and chemical samples were held at room temperature. Rainfall data was monitored and recorded throughout the study period at RDI, approximately 2 km from the studied communes.

Water analysis methods

Microbial analysis

Samples were analysed for Total Coliforms (TC) and *E. coli* by a modified membrane filtration technique using 47 mm filters (Millipore, Billerica, MA, USA) incubated on Rapid *E. coli* 2 Agar (BioRad, Hercules, CA, USA) for 24 h at 37°C. Enumerations were reported as CFU/100 mL. To test for male-specific coliphage (MsC) 1 L samples were filtered serially through a Whatman 47 mm filter (pore size 20–25 μm) to remove particulates and then a ViroCap 47 mm positive-charge filter (Scientific Methods, Granger, IN, USA). Filters were eluted with 5 mL of OptimaRE buffer (Scientific Methods) with 0.01% Tween 80 and standardised to 10 mL for analysis. Enumeration for male specific coliphage was performed using the double-agar layer (Adams 1959) with host *E. coli* F_{amp} and reported as PFU/10 mL eluate. For subsequent data analysis non-detect samples were reported as half the limit of detection.

Chemical analysis

Each sample was tested for a suite of parameters known either to be toxic to human health, or to impact the aesthetic quality of the water (Table 1). Health impacting contaminants included arsenic, fluoride, manganese, and nitrate; while aesthetic quality was determined by measuring iron, chloride, and total dissolved solids (TDS), hardness, conductivity and pH. Arsenic measurement was performed using the Econo-Quick™ Arsenic Kit (481298) for water quality testing (Industrial Test Systems Inc., Rock Hill SC, USA); results are reported discretely with a lower limit of detection of 5 ppb. All other parameters were measured using the Palintest® Photometer System model 7100 (Team Valley, Tyne & Wear, England) for water analysis.

Data analysis

Drinking water quality index

Data was tabulated according to RDI's Drinking Water Quality Index (DWQI) for comparison against the Cambodian drinking water standards (CDWS). The DWQI is a simple yet informative metric for the health and aesthetic conditions of the source water. Contaminants known to have a negative impact on human health are included in a health-based score scaled from 1 to 100 units, with unsafe scores being less than 60. Contaminants diminishing the aesthetic quality of the water are factored into a lettered grade, A to F. Contaminants that may be reasonably removed prior to consumption (Mn, Fe, *E. coli*) are conditionally referenced in the scoring, and a passing score is contingent upon their removal. Total coliforms and viral indicators were not included in the DWQI score. For each sample location and date, a DWQI rating (numerical score and letter grade) was generated.

Table 1 | Parameters included in the drinking water quality Index score and grade

Health contaminants	Cambodian drinking water standard	Rationale
Arsenic (As)	50 ppb	Long term exposure dermal lesions, peripheral neuropathy, various cancers (WHO set a standard of 10 ppb[*])
Manganese (Mn)	0.4 mg/L	Prolonged exposure to elevated concentration can cause adverse neurological effects
Fluoride (F)	1.5 mg/L	Concentration above 1.5 mg/L increases risk of dental fluorosis, and greater than 4 mg/L risks skeletal fluorosis
Nitrate (NO_3)	50 mg/L	Protective guideline against methaemoglobinaemia in bottle-fed infants
E. coli	0 cfu/100 mL	Presence suggests faecal contamination and the potential presence of pathogens causing diarrhoeal disease
Aesthetic contaminants[†]		
Iron (Fe)	0.3 mg/L	Higher concentrations can stain laundry and plumbing fixtures, impacting potential household uses
Manganese (Mn)	0.1 mg/L	Higher concentrations can stain laundry, food, and leave deposits on fixtures
Chloride (Cl)	250 mg/L	–
Conductivity	500 mg/L	–
Total Dissolved Solids (TDS)	800 mg/L	–
Hardness	200 mg/L	Increased concentrations reduce the effectiveness of detergents, and can scale metals (pipes, pans)
Turbidity	5 NTU	–
pH	6.5–8.5	–

[*] WHO (2008).

[†] Rationale listed is in addition to unpleasant taste and/or odour. Includes rationale relating to potential household uses of water.

The DWQI number was used to quantify the general quality of shallow aquifer water for household and drinking uses. To determine the influence season and well type had on water quality each data point was normalised by comparison to its national standard. Values less than one had contaminant levels below the CDWS, while those at or above one met or exceeded, respectively, the standard.

Statistical analysis

Descriptive statistics were performed using Excel 2003 SP3 (Microsoft Corp., Redmond, WA, USA). Non-parametric (Mann Whitney *U* test) comparisons for contaminants by season and well type were performed using Statistica v6.0 (Statsoft, Inc., Tulsa, OK, USA).

RESULTS AND DISCUSSION

Sixteen wells, after attrition of one RP well (land reclamation), were followed for 27 weeks from July 2008 through February 2009. Household surveys were carried out during the second week of sampling.

Household assessment

All wells followed were located on the users' property, reportedly reached 8–12 m into the shallow aquifer, and serviced a single household. The preferred water sources for households varied with the season and usage. An attempt was made to quantify the volume of water extracted from the wells; however, most estimates were crude from both well groups, with RP users often reporting "all day", and O well users unable to quantify water draw with any precision. An estimate of well activity was instead based on reliance on the well for household tasks. Shallow wells were the primary source of water for cleaning year round for all users. During the rainy season, both well types relied on harvested rain as their primary source for drinking and cooking water, and used well water occasionally to supplement stored rain water. In the dry season, six RP users relied on their wells for all uses, and three supplemented their well water with piped or bottled water for drinking. Of the open well users, only one household reported using the well as their sole source for drinking during the dry season; instead most relied on bottled water or stored rainwater.

With the exception of one household that only used their open well water for livestock and household cleaning, all reported boiling their drinking water prior to consumption. One household filtered water with a ceramic filter when not boiling, and three households reportedly practiced stand-and-settle techniques prior to boiling. All households visited during the week of survey had stored raw water in the home; it is likely that households are unknowingly practising a form of stand-and-settle. No household used water from the deep aquifer for any purpose. Households were aware of the elevated arsenic levels in water from tube wells, and most were aware of at least one symptom of arsenic poisoning.

The economic status was similar between O and RP well users. Households ranged from three to 17 residents (median = six) and were subsisting at the Cambodian national poverty line: income and expenditure average USD 3 per person per day for both O and RP well users. Environmental characteristics that may impact water quality were also similar by well type. Ten households (five O, five RP) had livestock (chickens, cows, pigs or a combination thereof) on the property, most within 25 m of the wellhead. 18 households reported simple squat pit latrines and two households shared these facilities with neighbours; one household of seven residents practiced open defecation.

Water quality

Quality of water from the shallow aquifer

The measured values for each well at each date were compared to the Cambodian drinking water standards to determine the relative quality of the water for household use. The overall relation of contaminants to standards was aggregated to determine a DWQI rating, composed of a numerical score and letter grade. Figure 1 depicts the DWQI health score by well for all sampling. The average DWQI rating for the shallow aquifer over the 27 weeks of study was 71F. Twenty-five percent of all samples ($n = 246$) were found to be unsafe for consumption, the remaining were either conditionally safe (with *E. coli*, manganese/iron, or turbidity exceeding standards), or had *E.coli* levels

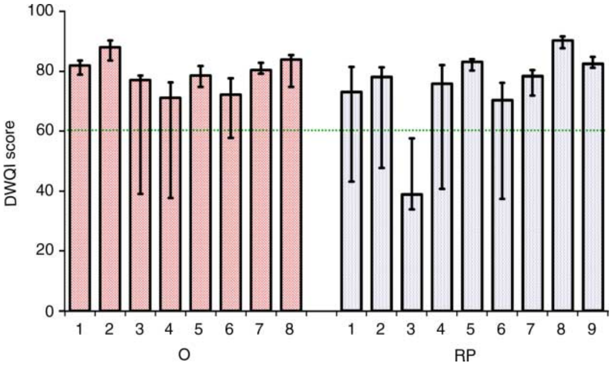

Figure 1 | Health Related Rating by Well. Plotted are median scores with interquartile range. For all wells $n = 15$, except RP 7 where $n = 6$. ▦ = Open well, ▨ = Rope-pump well, ■ ■ ■ = passing threshold.

at the limit of detection for the sample volume. The overall quality of water between open and rope-pump wells was similar. Open wells averaged a rating of 73F, with 18.3% of samples ($n = 120$) deemed unsafe. Rope-pump wells were rated with 69F, and 31.7% of samples ($n = 126$) were unsafe. The discrepancy between failure rates is a reflection of the increased variability in rope-pump water quality. All samples (for every site and sampling date) received a failing DWQI grade for aesthetics, indicating that the water was potentially undesirable for consumption based on the exceedance of drinking water quality standards.

In 2005 the water quality from tube wells reaching into the deep aquifer within the study area was determined by RDI. All tube wells measured exceeded CDWS for arsenic ($n = 1$), manganese ($n = 4$), or for both chemicals ($n = 20$). For Preaek Aeng the average DWQI rating was 1F (RDI 2008*a*), and in Kbal Kaoh the average rating was 10F (RDI 2008*b*), evidence that the shallow aquifer is chemically more safe than the deep aquifer. This is largely due to lower arsenic contamination: 1.6% of samples (three O and one RP well) were contaminated to levels at the CDWS, yet still 13% met or exceeded the WHO standards. Manganese levels were also improved compared to the deep aquifer, with a 16% failure rate compared to 92% for the deep aquifer. DWQI ratings at the commune level are part of a greater statistical model than those used in this study, and represent the probability of encountering safe water in a given commune for a well depth. While not directly comparable to individual DWQI rating for the shallow aquifer, they do provide means of assessing the relative contamination loads between aquifers.

Temporal variation in water quality

The sampling period was divided into a rainy season lasting 13 weeks (eight samples) and having a cumulative measured rainfall of 1,059 mm, and a dry season covering 14 weeks (seven samples) with 131 mm of rainfall. The water quality varied significantly for the majority of parameters from the rainy to the dry season. Water hardness, conductivity, and TDS, while already exceeding acceptable aesthetic levels, significantly (Mann-Whitney *U* test, $p < 0.05$) increased during the dry season. Nitrate levels also increased during the dry season with RP 3 and 4 consistently exceeding CDW health standards. Data normalised to the CDWS is presented in Figure 2. Temporal differences in other health related chemical parameters such as As, F, and Mn were not significant. Fluoride contamination was below health standards (exceedance <1%) for the entirety of the study period and variation in manganese levels was not associated with temporal changes.

Microbial contamination decreased significantly ($p < 0.05$) during the dry season for TC, *E. coli*, and MsC (Figure 3). Even with decreased loads, wells were grossly contaminated with TC and *E.coli* throughout the study period, and considerably contaminated with MsC during the rainy season. Median TC contamination was $10^{4.3}$ CFU/100 mL for the rainy season; in the dry season there was a half $\log_{10}$ reduction in contamination and an overall decrease in the variability found between samples. *E. coli* median contamination was $10^{3.2}$ CFU/100 mL and decreased by one $\log_{10}$ into the dry season. MsC were

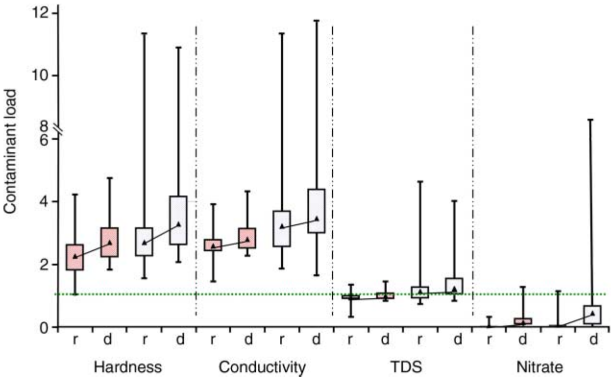

Figure 2 | Normalised Load for Selected Contaminants. Contaminant level by well type and season. Shown are median, interquartile range, minimum and maximum values for each cluster. $r =$ rainy season, $d =$ dry season. ▦ = Open Well, ▨ = Rope-pump Well, ■ ■ ■ = CDWS.

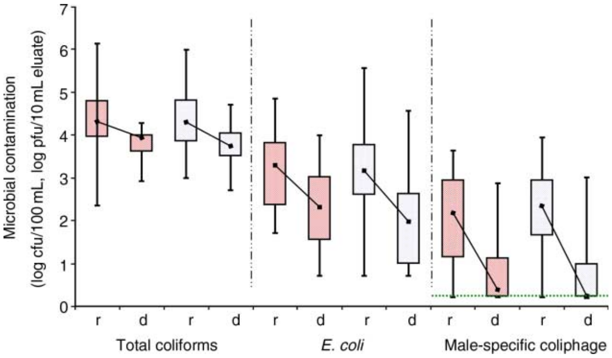

Figure 3 | Microbial Quality. Contaminant level by well type and season. Shown are median, interquartile range, minimum and maximum values for each cluster. *r* = rainy season, *d* = dry season. ▦ = Open Well, ⊡ = Rope-pump Well, ▦ = LLOD.

present at $10^{2.2}$ PFU/10 mL eluate, representing the virus recovered from one litre of filtered water. Minima and maxima values during the dry season are upper and lower limits of detection for *E.coli*, and lower limits of detection for MsC, and as such do not represent the true variability in the water samples. The trend witnessed in this data set, a universal decrease in microbial contamination during the dry season, is similar to results by Barrell & Rowland (1979) who found ten- to 100-fold increases in well water contamination with faecal coliforms following the onset of rains. Rainfall during the first 4 months of this study was greater than the regional average for previous years (Hisakane *et al.* 2008). These excessive rains may have contributed to elevated levels of microbial pollutants.

Water quality by well type

Rope-pump wells do not appear to provide water quality improvement over traditional open wells. The amendments made to an open well to create a rope-pump well are designed to improve ease of access to water, prevent gross contamination of the well by capping the well head, and to dampen seepage of contaminants into the well by facilitating their removal from the well casing with a cement apron and drain. Such amendments would have little impact on the specific parameters tested and do not appear to be "protected from outside contamination". RP well contamination was greater than O wells for many parameters; differences were statistically significant (Mann Whitney U test, $p < 0.05$) for the aesthetic parameters of hardness, conductivity, and total dissolved solids throughout the study period, and nitrate in the dry season (Figure 2). The variability of these contaminants was also greater for RP wells, which is not attributable to any one well. Microbiological contamination within a season was not significantly different between well types; both O and RP wells were similarly contaminated with high levels of TC and *E. coli* throughout the study, and also had similar MsC levels throughout.

While the wells in this study are presumed to be accessing the same aquifer, this assumption was not tested. Given the variability in water quality of the deep aquifers it is possible that many aquifers were represented by these samples.

In this study region the prevalence of arsenic contamination in the deep aquifer necessitates reliance on the shallow aquifer for safe household water. The lack of significant difference in the quality of improved and unimproved sources, and the findings that both well types had considerable microbial contamination, suggests that point of use treatment is a more appropriate investment than upgrading from an unimproved to an improved shallow aquifer source. Assessment of various point of use technologies has been performed elsewhere (Fewtrell *et al.* 2005; Clasen *et al.* 2007; Brown *et al.* 2008). All households reported at least boiling their water before consumption, and if done properly this would sufficiently improve the microbial quality of the water. Chemically the shallow aquifer was also found to be unsafe due to manganese (16% failure rate) and nitrate (8%) contamination. Manganese contamination can be mitigated by point of use treatment technologies that foster aeration, to promote oxidation of manganese to its insoluble form, and filtration. Nitrate contamination was predominantly of concern only for RP 3 and 4, which contributed 74% ($n = 19$) of the samples exceeding the CDWS, and does not appear to be widespread contamination of the aquifer. It is more likely that such elevated levels are a result of localised human disturbances including poor waste management and dense livestock activity.

CONCLUSIONS

The shallow aquifer is an appealing alternative to the deep Cambodian aquifer that is often contaminated with arsenic in regions near the Mekong and Bassac Rivers. Investigation into the quality of water from the shallow aquifer demonstrated that it is primarily contaminated with pollutants that may be removed prior to consumption, such as manganese and *E. coli*. However, there is no significant difference in the water quality from open wells and rope-pump wells despite their classification by the WHO/UNICEF JMP as unimproved and improved respectively. Additionally, rope-pump systems are commonly installed upon existing open wells; therefore neither the proximity to, nor quantity available from, the source is improved. Ease of water draw from rope-pumps may facilitate the use of larger volumes of water, thereby improving hygiene for a household, but does not necessarily provide access to "safe water". When promoting technologies to the economically developing world it is important that the desired impact is realised, and not merely assumed, especially when capital investments are required to facilitate technological "improvements".

ACKNOWLEDGEMENTS

Financial support for this work was provided in part by the Washington Global Health Alliance and The Collaborative Center for Healthy Work, Grant #: NIH 5D43TW000642-13. We thank Dr. Fu-Chih Hsu for his contribution of materials. The authors are grateful for the support of RDI staff including Ms. Laingshun Huoy and Ms. Kunthy Sok among many others.

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