Drinking Water Quality & Point-of-Use Treatment Studies in Nepal

Since the majority of Nepalese drinking water is contaminated, it should undergo filtration to remove turbidity followed by disinfection to inactivate microbes.

ANDY BITTNER, AMER M.A. KHAYYAT,
KIM LUU, BENOIT MAAG,
SUSAN E. MURCOTT, PATRICIA M. PINTO,
JUNKO SAGARA & ANDREA WOLFE

Nepal has abundant freshwater resources including springs, rivers and groundwater supplies; however, drinking water quality varies greatly. Only 34 percent of Nepal's population has access to safe drinking water.[1] (The statistics on this point vary widely. The Nepal Human Development Report in 2001 cites a survey estimating that 80 percent of Nepal's population has access to piped or tubewell water.[2]) Most settlements and households do not have access to piped water. In the urban areas such as the capital, Kathmandu, access to piped water is available to only 58 percent of urban households.[3] Table 1 shows the distribution of households by source of drinking water.

There are three distinct geographic regions in Nepal: the southern plains, the hills and the Himalayas. The plains region, called the Terai, is densely populated and has heavy industrial and agricultural activity. In the Terai, much of the drinking water comes from groundwater wells. The hills lie between the plains and the mountains. This region is also densely populated and contains the major cities, including Kathmandu. Drinking water sources in the hills include both surface water and groundwater. The population of the mountainous Himalayan region is sparse and often migratory. In this region, drinking water comes mostly from springs and surface water sources.

Drinking Water Quality

Drinking water was studied in the Kath-

TABLE 1.
Distribution of Households by Source of Drinking Water

Sources of Drinking Water	Rural (%)	Urban (%)
Piped Water	29.1	57.4
Well Water	7.0	8.7
Hand Pump	33.3	27.3
Spring Water	20.8	0.0
River/Stream	7.6	3.3
Stone Tap	1.6	1.8
Other	1.7	1.5

Note: Data are from Ref. 3 as is.

mandu Valley and the Terai region for microbial, arsenic, nitrate and ammonia contamination. Nearly 200 groundwater and surface water samples were collected from various source types, including municipal systems and from traditional sources such as water spouts, hand-dug wells and tube wells.

Microbial Contamination. Microbial contamination studies focused on drinking water in the Kathmandu Valley using bacterial indicator organisms. While waterborne pathogens may be bacteria, viruses, protozoa or helminthes, analytic methods to test for bacterial indicator organisms were chosen because these tests are simple, inexpensive and potentially easily transferable. However, the absence of these bacterial indicators does not ensure that the water will be free of pathogens. Enteroviruses, giardia, amoebas, ascaris and cryptosporidium — all prevalent in Nepal — are not necessarily correlated with bacterial levels. Moreover, these microorganisms are more resistant to disinfection. Nonetheless, bacillary dysentery and gastroenteritis — both bacterial in origin — are common in Nepal, and for this study only bacterial indicators were used.

In the Kathmandu Valley, drinking water sources are varied and water quality often changes dramatically between source and consumption. Urban drinking water is collected from surface water or groundwater sources and about 60 percent of Kathmandu's water supply is treated at a municipal water treatment plant before being distributed through a piping network to households and street taps for collection. Many users collect their water from these public taps. In some areas, water is collected directly from a source, such as a tube well or spring, and then distributed without treatment. The goal of the microbial portion of the overall study was to determine the prevalence and main locations of microbial contamination, using bacterial indicator organisms, and to determine if the water met World Health Organization (WHO) guidelines.

WHO guidelines state that drinking water must not contain waterborne pathogens.[4] More specifically, *E. coli* or thermotolerant coliforms should not be present in 100 milliliter (mL) samples of drinking water at any time, for any type of water supply (treated or untreated, piped or un-piped). In the case of large supplies, where sufficient numbers of samples are examined, total coliforms are acceptable in the distribution system in a maximum of 5 percent of the samples taken throughout any 12-month period.[4] WHO further specifies that although *E. coli* is the more precise indicator of fecal pollution, the count of thermotolerant coliform bacteria is an acceptable alternative. In contrast, total coliform bacteria are not ideal indicators of the sanitary quality of rural water supplies, particularly in tropical areas where many bacteria of no sanitary significance occur in almost all untreated supplies.[5] In light of the WHO guidelines, tests were conducted for three indicator organisms: total coliform (because it is the most standard microbial test, in spite of the above-mentioned shortcomings), *E. coli* and hydrogen-sulfide–producing bacteria.

Arsenic Contamination. Arsenic is a highly toxic chemical with wide-ranging acute and chronic health effects that depend on the duration and extent of exposure. The WHO has set the maximum contaminant level for arsenic at 10 parts per billion (ppb) and His Majesty's Government of Nepal has set an "interim" arsenic standard of 50 ppb. Due to the current crisis of arsenic contamination in the neighboring countries of Bangladesh and India, the geology and hydrology of Nepal suggest that arsenic may be a problem there, too, in areas where tube wells are used as the primary source of drinking water. Therefore, it would be necessary to determine the extent of arsenic contamination in these regions of Nepal and to make recommendations for future monitoring and testing.

Nitrate & Ammonia Contamination. Environmental nitrates in groundwater have been linked to anthropogenic sources such as septic systems, agricultural fertilizers and inadequate treatment and disposal of sewage wastes. Nitrates in drinking water can cause methemoglobinemia, or "blue-baby" syndrome, in infants less than a year of age. The WHO has set a limit of 10 mg/L NO_3-N based on the occurrence of "blue-baby" syndrome. The WHO has also set a limit of 1.5 mg/L NH_4^+-N because ammonia generally accompanies human and animal waste and is, therefore, an indicator of microbial contamination. Due to the use of environmental nitrates in Nepal, it was necessary to assess potential groundwater contamination due to nitrates and ammonia in drinking water supplies in urban and rural areas.

Methods

Samples taken in the Kathmandu Valley were analyzed for turbidity and microbial contamination. Turbidity was measured using a turbidimeter. Microbial samples were analyzed using both presence/absence (P/A) tests that indicate total coliform and *E. coli* presence and hydrogen sulfide (H_2S) tests. The hydrogen sulfide test is a color change, most probable number (MPN) test. For each set of tests, a blank was run using either distilled or bottled water to ensure that laboratory practices did not contaminate the samples. The hydrogen sulfide test was selected for use to complement the total coliform and *E. coli* tests for several reasons. First, the hydrogen sulfide test is less sensitive to temperature changes during incubation, thus in tropical climates it can potentially be incubated at ambient temperature without the need for an electric incubator. Second, this test appears to be the most simple and least expensive microbial test, and it might be potentially transferable to Nepali colleagues for wide-scale water quality monitoring, especially in remote regions or at sites lacking electricity for incubation. Third, in tropical climates, coliform bacteria are able to multiply in the soil environment. Since most sewage-borne pathogens cannot multiply in the environment, coliform bacteria are not a reliable test in tropical climates and, hence, in many developing country contexts.[6] However, the presence of coliform bacteria does not interfere with the hydrogen sulfide test, making the test a valuable alternative to traditional coliform indicator tests.

Test strips, concentration kits and graphite furnace atomic absorption spectroscopy (GFAAS) were used to analyze arsenic concentrations in the drinking water samples. The test strips have a detection limit of 100 ppb, well above the WHO standard of 10 ppb. Due to this, concentration kits were also used in conjunction with the test strips to achieve a detection limit of 10 ppb. GFAAS has a minimum detection limit of 5 ppb and is a more accurate measure of arsenic concentration than the field kits. A portion of each sample was preserved to 1 percent acidification and sealed in plastic tubes for transport back to the Massachusetts Institute of Technology (MIT), where they were analyzed on the GFAAS unit at the Ralph M. Parsons Laboratory.

Drinking water samples were tested for nitrates using the cadmium reduction method. Samples were tested for ammonia using the ammonia salicylate method. Analyses were performed using two spectrophotometers.

Results & Discussion

Microbial Contamination. Drinking water was sampled from a wide range of locations in and around Kathmandu and drinking water source types were divided into several categories for analysis. The different source types included well and stream sources, influent and effluent treatment plant samples, source distribution points and consumption points. Consumption points included samples taken from drinking water in restaurants and stores within Kathmandu. All samples were tested for turbidity, total coliform, *E. coli* and/or hydrogen-sulfide–producing bacteria.

Figure 1 shows how the level of microbial contamination varies throughout the Kath-

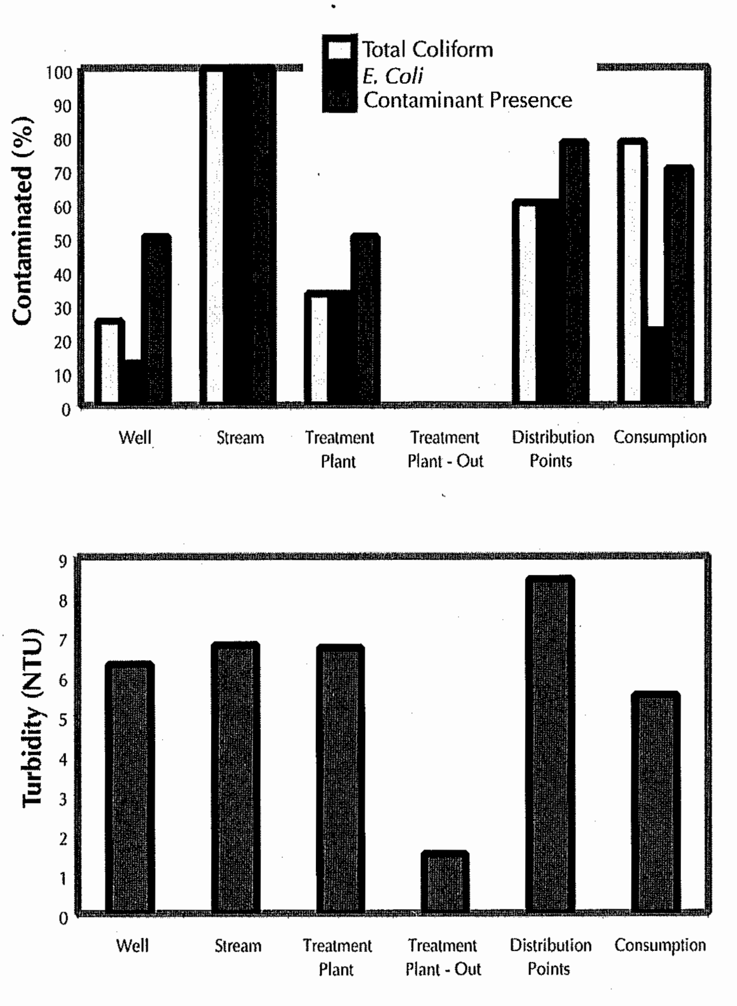

FIGURE 1. Microbial contamination and turbidity levels for January 2000.

mandu Valley water supply system. "Contaminant presence" indicates the detection of any type of contamination in the sample, either total coliform, *E. coli* or hydrogen-sulfide–producing bacteria. The numbers of samples analyzed for each of the various points in the water distribution system are shown in Table 2.

Different microbial contamination levels were found in samples from surface water and groundwater sources. Tube wells, which supply users with groundwater, generally had better water quality than the other sources, although more than 50 percent showed contaminant presence. Samples were collected within the treatment plant system at several different stages of treatment. Although raw water flowing into the treatment plants and water at differing stages of treatment was also contaminated 50 percent of the time, no samples taken at the outflow of the treatment

TABLE 2.
Number of Samples Analyzed

Source	Turbidity	Total Coliform	*E. Coli*	Contaminant Presence
Well	8	8	8	8
Stream	4	3	3	4
Treatment Plant	4	3	3	4
Treatment Plant — Out	3	3	3	3
Source Distribution Points	10	5	5	10
Consumption Points	10	9	9	10

Note: Total number of samples is 39.

plants had total coliform, *E. coli* or hydrogen-sulfide–producing bacteria contamination. This lack of contamination was largely because all treatment plants were using chlorination as the final step in the treatment process.

Even though the treated water was found to be free of total coliform, *E. coli* and hydrogen-sulfide–producing bacteria, the source distribution points were not. This finding indicated that water became contaminated within the distribution system. Almost 80 percent of the samples taken at source distribution points showed microbial contamination. There were few differences between the contamination at the source distribution points and the consumption points, which suggested that additional contamination did not occur beyond the source distribution points. This lack of difference was perhaps because people in Kathmandu restaurants and stores that were sampled used some form of simple household treatment such as filtration and/or boiled water supplies.[7]

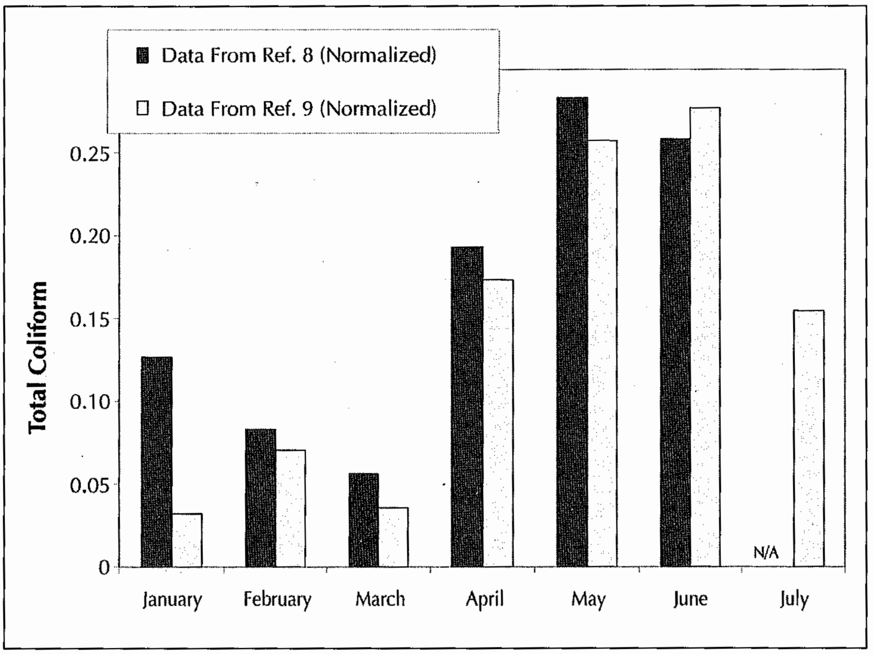

FIGURE 2. Seasonal variation of total coliform in the Kathmandu Valley water distribution system.

The turbidity data showed that average turbidity levels in the wells, streams and treatment plants during the three-week field study in January 2000 were about the same — 6 to 8 nephelometric turbidity units (NTUs) Turbidity was low at the treatment plant outlet (1.5 NTU) but increased at the distribution points (8.5 NTU). These results reinforced the theory that contamination occurred within the distribution system. Lower average turbidity was found at commercial consumption points (5.5 NTU), perhaps due to household filtration and/or boiling.

One of the main problems with water quality in Kathmandu is that it varies drastically over the course of the year. In the dry season there are often fewer incidences of pollution in the water supply system than in the wet season when microbial contamination increases significantly. Figure 2 shows some of the cyclical variations in total coliform levels in the Kathmandu Valley water distribution system.[8,9] Data were normalized to provide a better seasonal comparison. The results indicated a pattern of contamination that made high contamination levels predictable, according to season.

Arsenic Contamination. A total of 172 samples from various sources were analyzed for the presence of arsenic. The samples were taken from four main locations: the Parsa, Bara, and Lumbini Districts in the Terai region; and from the Kathmandu Valley. Figures 3 to 5 summarize the results obtained in each of these locations based on the three different analytical methods used: the two field test methods (test strips and concentration kits) and the laboratory method (GFAAS).

The data in each of the figures show that no arsenic levels above the WHO limit were found in the Kathmandu Valley. Most of the

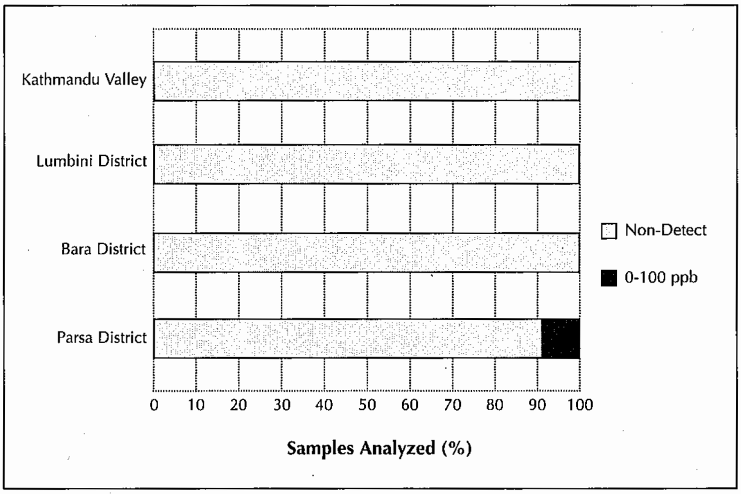

FIGURE 3. Test strip results for Arsenic contamination.

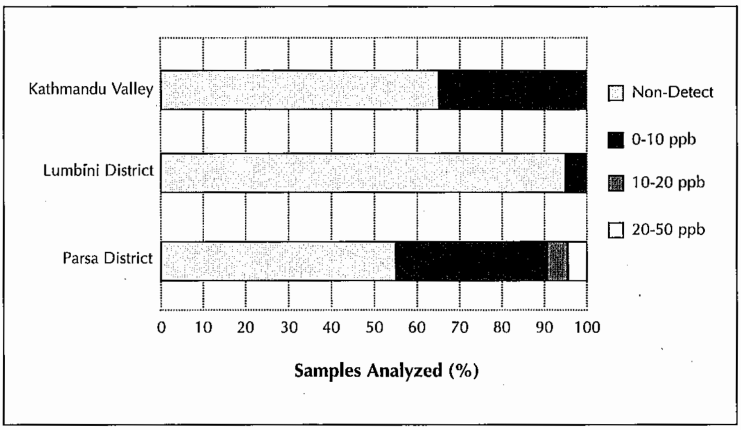

FIGURE 4. Concentration kit results for Arsenic contamination.

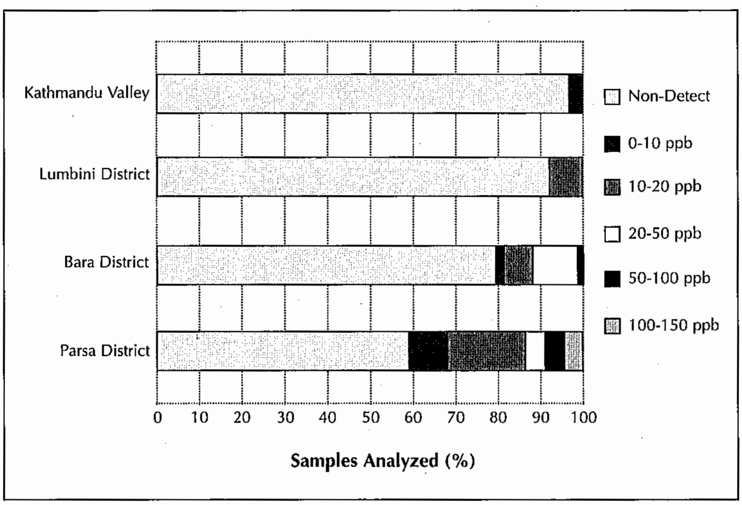

FIGURE 5. GFAAS results for Arsenic contamination.

water sources sampled in the Kathmandu Valley were municipally supplied water, hand-dug wells and traditional stone spouts. The figures also show that concentrations above the WHO limit were found in a portion of the samples taken from the Terai region. These samples were from tube wells operated with hand pumps. Results from the GFAAS method, the most accurate of those used, indicated that 18 percent of the samples analyzed from the Terai region were above the WHO limit.

Results for the different test methods varied. For instance, 100 percent of the Bara District samples were non-detect when analyzed with the test strips. However, 20 percent of samples contained detectable levels of arsenic when analyzed with GFAAS. Far greater accuracy is associated with the GFAAS method. Although the accuracy of the test strips was questionable (based on these data), it provided a general indication of arsenic concentrations in the field. When the test strips were used with the concentration kits, a more sensitive and reliable field measurement could be obtained. However, field kits should be used in conjunction with more accurate laboratory methods if more precise arsenic measurements are required.

Figure 6 shows the depth variation of arsenic contamination. Detectable levels of arsenic were found in wells up to 300 feet deep. These depths correspond with a

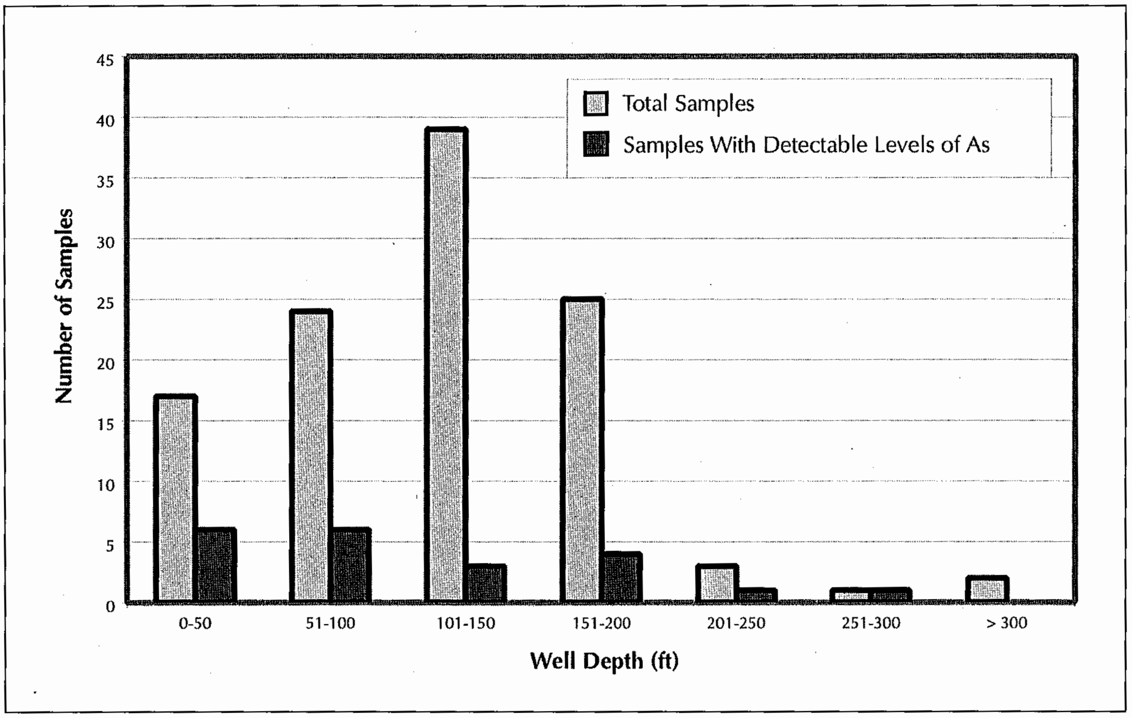

FIGURE 6. Sample frequency by well depth for Arsenic contamination.

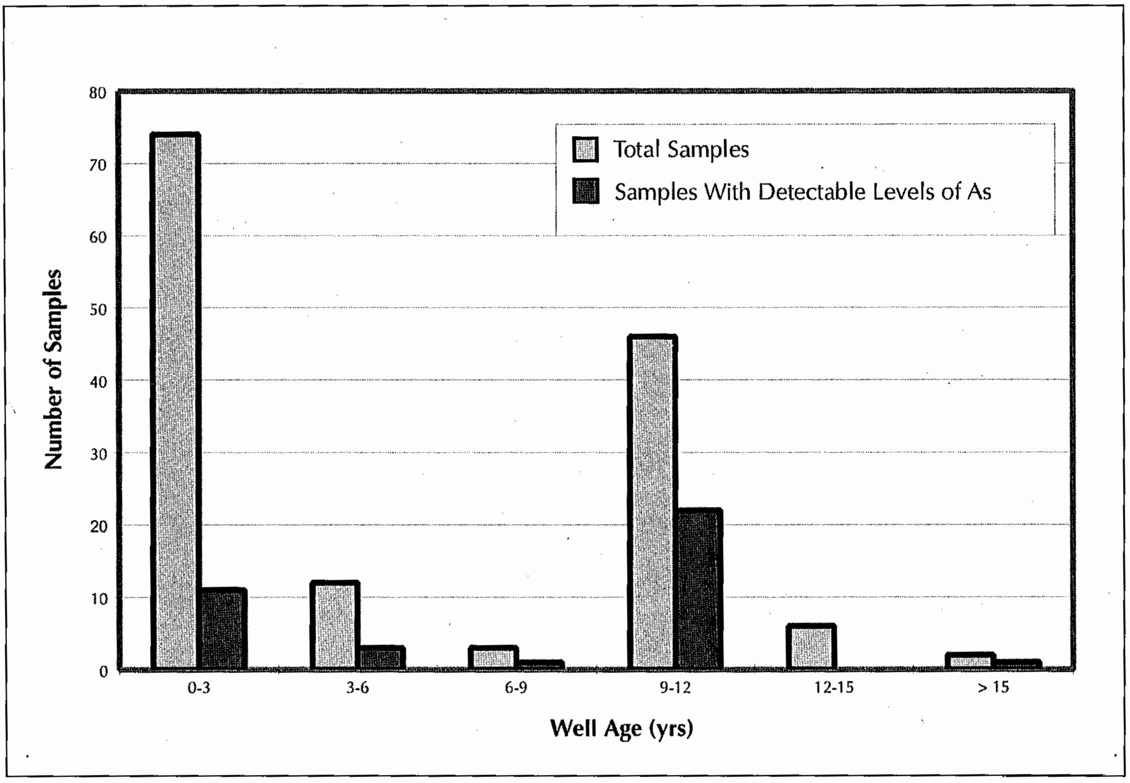

FIGURE 7. Sample frequency by well age for Arsenic contamination.

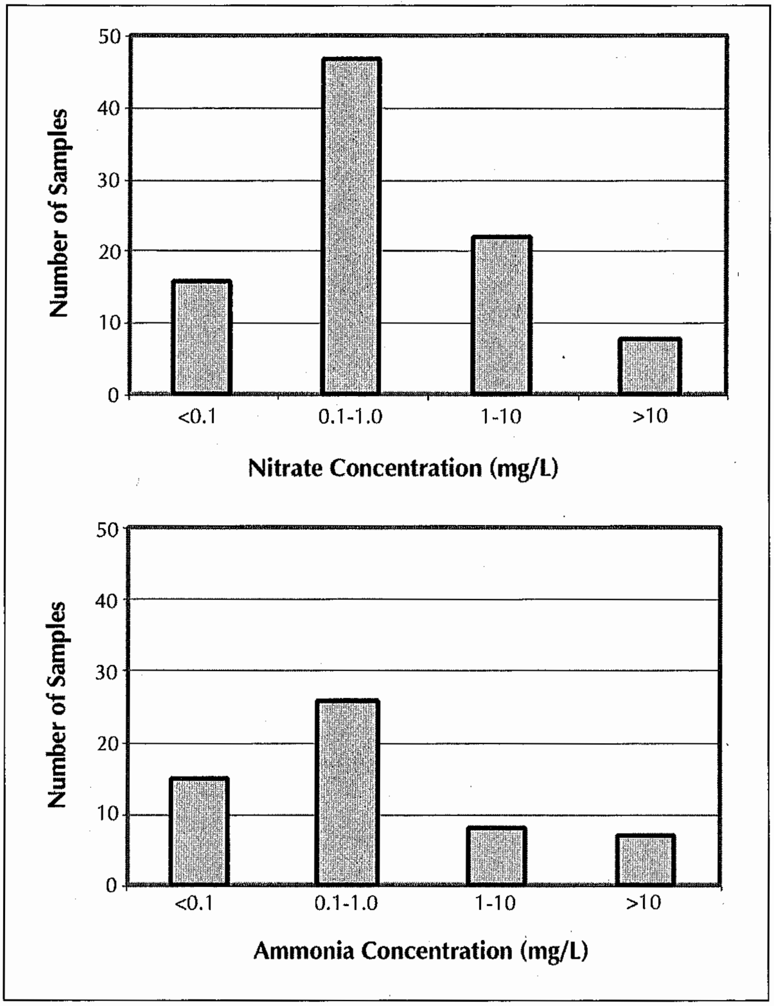

FIGURE 8. Nitrate and ammonia concentrations.

thick top layer of alluvial deposits in the Terai region similar to the geology of areas with arsenic contamination in Bangladesh and West Bengal. Some of these alluvial deposits are from the same rivers that flow through the contaminated areas in Bangladesh and India. The deposits, therefore, could be from the same arsenic-rich sources as in these countries, suggesting that the arsenic contamination that was found may be of natural origin.

Figure 7 depicts the well age variation of arsenic contamination. Forty-eight percent of the samples taken from wells 9 to 12 years old contained detectable levels of arsenic. An explanation for this finding may be that extensive drawdown of the water table associated with long-term operation of a well was causing a change in subsurface chemistry. Consequently, the change in water table height may result in a conversion of immobile species to more mobile arsenic species that leave solid substrates to enter the groundwater.

Preliminary analysis of the data presented in Figures 6 and 7 indicated that arsenic contamination in the Terai is of natural origin. Recommendations to further characterize the Terai region include further testing, study of the geology and analysis of potential anthropogenic sources.

Nitrate & Ammonia Contamination. Groundwater samples were collected and analyzed for nitrates and ammonia from a variety of source types including tube wells, deep boring wells and traditional water spouts. Samples were collected from rural, agricultural, industrial and urban areas. Figure 8 shows the concentrations of nitrates and ammonia. The average nitrate concentration was 2.37 mg/L NO_3-N. Nine percent of all samples were contaminated with nitrate levels above the WHO guideline. The average ammonia concentration was 5.2 mg/L NH_4^+-N. Twenty-nine percent of all samples were contaminated with ammonia concentrations above the WHO guideline.

The data showed that the nitrate contamination of groundwater generally occurred in wells shallower than 50 feet. A sufficient amount of available carbon, along with an absence of oxygen in deeper regions, caused microbes to denitrify any available nitrates, thus producing nitrogen gas. Nitrate contamination at shallow depths was apparently anthropogenic in origin, due to agricultural fertilizers and inadequate human and animal

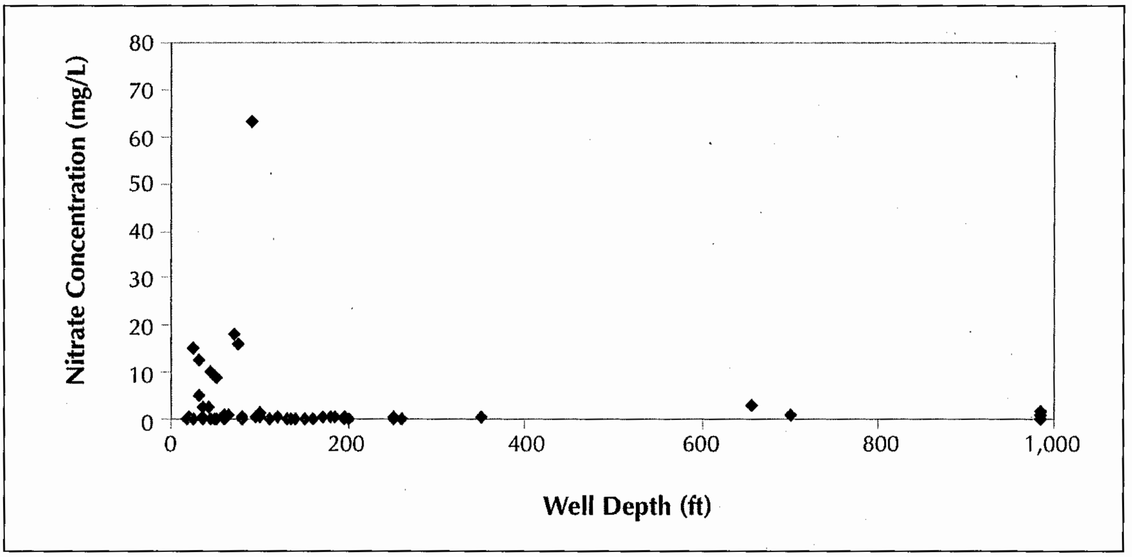

FIGURE 9. Nitrate concentration versus well depth.

waste disposal practices. Nineteen percent of samples from wells shallower than 50 feet were contaminated with nitrate levels above the WHO limit. No wells deeper than 100 feet were contaminated with nitrate concentrations above 1 mg/L NO_3-N. The depth variation of nitrate concentrations is shown in Figure 9.

Figure 10 shows ammonia concentration versus depth. Ammonia contamination was minimal in the shallow wells because, in the presence of oxygen, ammonia will nitrify. However, high ammonia concentrations existed in the deep aquifers due to geologic depositions of peat and lignite. There was insufficient oxygen at these depths to nitrify the ammonia. In the Kathmandu Valley, deep boring wells were normally 600 to 900 feet deep. Sampled deep boring wells contained ammonia at an average level of 48 mg/L NH_3-N (well above the WHO limit for ammonia). Samples from all other sources had negligible ammonia concentrations.

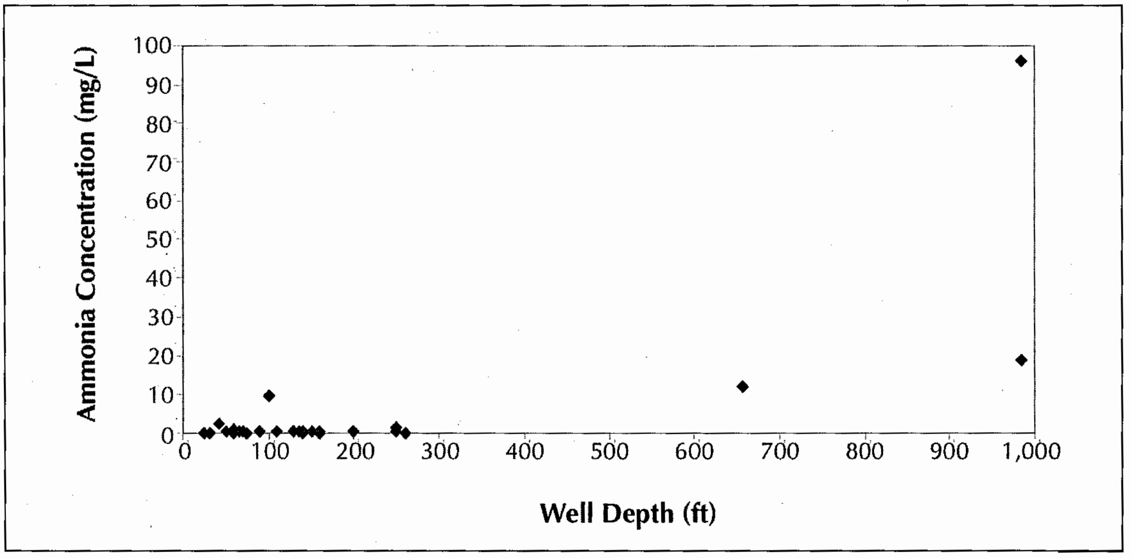

FIGURE 10. Ammonia concentration versus well depth.

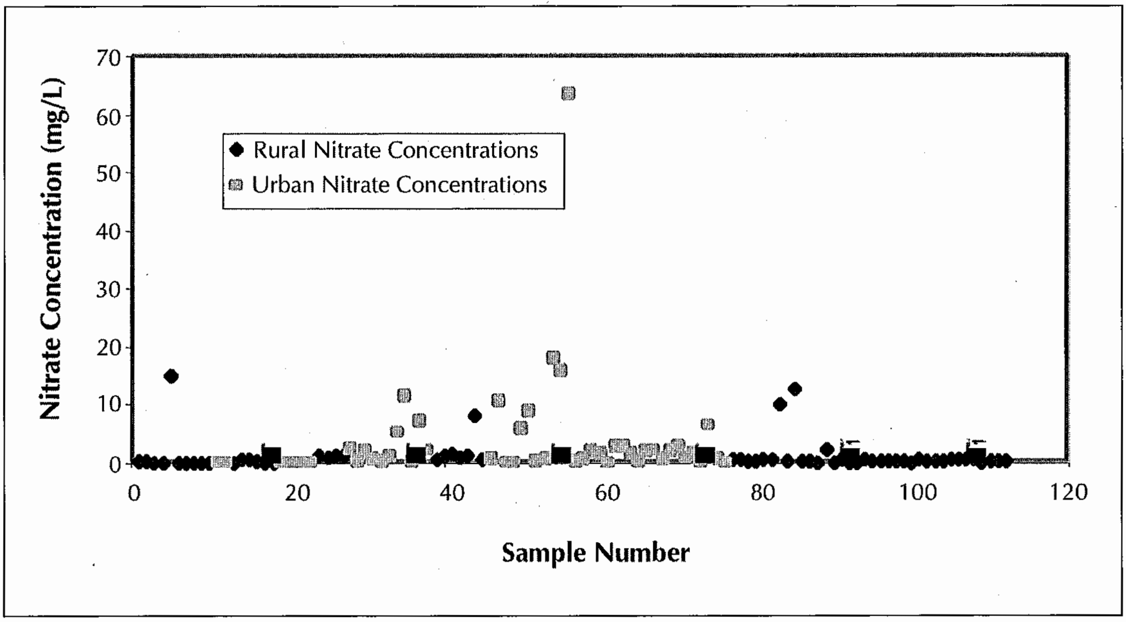

FIGURE 11. Nitrate concentration in urban versus rural regions.

Figure 11 shows nitrate concentrations from groundwater samples in both urban and rural areas. Nitrate contamination in Nepal was much more prevalent in urban areas than in rural agricultural regions. The average urban nitrate concentration was found to be 3.9 mg/L NO_3^--N and 10 percent of the urban samples contained nitrate concentrations above the WHO limit. Septic systems, inadequate sewage treatment and animal waste are typical urban anthropogenic sources of nitrates. All three sources were possible in Kathmandu, where septic systems were commonly used, wastewater treatment was practically non-existent and animals, especially cattle, roamed the streets freely. The main rural anthropogenic source of contamination was from nitrate fertilizers leaching into soil and groundwater. The average rural nitrate concentration was 1.2 mg/L NO_3^--N. Only 5 percent of the rural samples contained nitrate levels above the WHO guideline. Low rural nitrate contamination may be due to dry season conditions that cause reduced infiltration and surface runoff. However, sampling was only performed during the dry season. Sampling during both the dry and monsoon seasons is recommended to determine if nitrate concentrations in groundwater from rural areas is consistent year-round.

Point-of-Use Treatment Study

One in ten children in Nepal die before the age of five,[10] and the majority of these deaths are caused by waterborne diseases. The current state of the economy (Nepal is the seventh poorest country in the world[11]) and infrastructure in Nepal makes attempts to achieve widespread coverage by centralized water treatment systems unfeasible and prohibitively expensive. Point-of-use (POU) household water treatment systems might be an alternative to centralized treatment systems. The main objective of this year-long project was to identify key water quality parameters and then to try to develop an appropriate POU system that would be within the economic reach of all Nepalese citizens. POU treatment options were analyzed according to the following criteria: viability, cost and equipment availability.

The three most basic unit processes of a conventional centralized water treatment facility are coagulation, filtration and disinfection. Each of these processes was reconceptualized and adapted for POU applications. Coagulation and settling is the first step for removing raw water turbidity and color. Filtration takes out particulate matter in addition to reducing microbial contamination. Disinfection is designed to reduce or eliminate pathogens.

Coagulation. Coagulation and settling experiments were performed using a mechanized flocculator. Manual coagulation experiments applying optimum alum doses determined by conventional jar test procedures were then tested to determine the effectiveness and practicality of this non-mechanized approach for rural Nepal. These tests were conducted using materials locally available in rural Nepalese villages. The results of these experiments determined the applicability of manual coagulation with a POU treatment regime.

Filtration. Filtration is a simple and effective method of treating drinking water. Three filter/purifier batch "pour-through" systems — including one that is currently manufactured in Nepal, one that is manufactured in India and imported to Nepal, and one that is manufactured in Haiti and which was brought to Nepal — were studied as possible drinking water filtration options for Nepalese households. The filtration media in the Nepalese and Indian systems are ceramic candles composed of fine white clay. The Haitian filter has two filtration elements: a cotton strung-wound rough filter followed by a granular activated carbon filter. This filter also employs chlorine disinfection. These systems were tested for their efficiency in removing turbidity and microbial contamination.

Disinfection. Three disinfection options — chlorination, ultraviolet and solar — were initially proposed and evaluated. Ultraviolet disinfection proved unfeasible due to unreliable electric power supply in Nepal. Chlorination also proved impractical because chlorine is not readily available in Nepal. (Subsequent work by graduate students at MIT has involved the import, set-up and operation of a sodium hypochlorite generator at the Environment and Public Health Organization [ENPHO] laboratory in Kathmandu, Nepal.[12]) Thus, the solar disinfection option became the primary focus. Research into the field of solar water disinfection was initiated by a group of scientists at the American University of Beirut in the late 1970s.[13] Researchers at the Swiss Federal Institute have performed the most extensive field testing of this method to date.[14] Although there has been an independent field trial conducted in the Terai region by Peter Moulton, no previous solar disinfection tests had been performed in the Kathmandu Valley.

Methods

The water used for each test was bacterially contaminated tap water supplied by the Sundarighat treatment plant. (The treatment plant water is contaminated because of poor operation and maintenance and sporadic or nonexistent chlorine disinfection.) The coagulation, filtration and disinfection studies measured removal efficiencies of turbidity using a turbidimeter. Filtration and disinfection studies measured removal efficiencies of microbial contamination using the same methods outlined in the microbial portion described earlier.

Coagulation and settling experiments were performed using two different types of imported Indian alum taken from the Bansbari and Mahankal water treatment plants in Kathmandu. Raw water samples were dosed with a 2 percent dissolved alum solution. Experiments to determine the optimum dose, using both mechanized and manual stirring adapted to imitate mechanized stirring, were conducted under a mixing regime of 30 seconds of rapid mix at 100 revolutions per minute (rpm), 10 minutes of slow mix at 30 rpm and a settling period of 30 minutes.

Solar disinfection tests were conducted on the south-facing black-tarred roof of the Nepal Water Supply Corporation Central Laboratory. Three locally available 1.5-liter bottle types were tested: untinted transparent plastic, blue-tinted transparent plastic and untinted transparent glass. Solar intensity was logged hourly using a pyranometer/datalogger that was responsive to wavelengths between 350 and 1500 nanometers (nm). Bottle transmissivity tests were conducted at MIT.

Results & Discussion

Coagulation & Settling. Two locally available types of alum were tested from the Bansbari

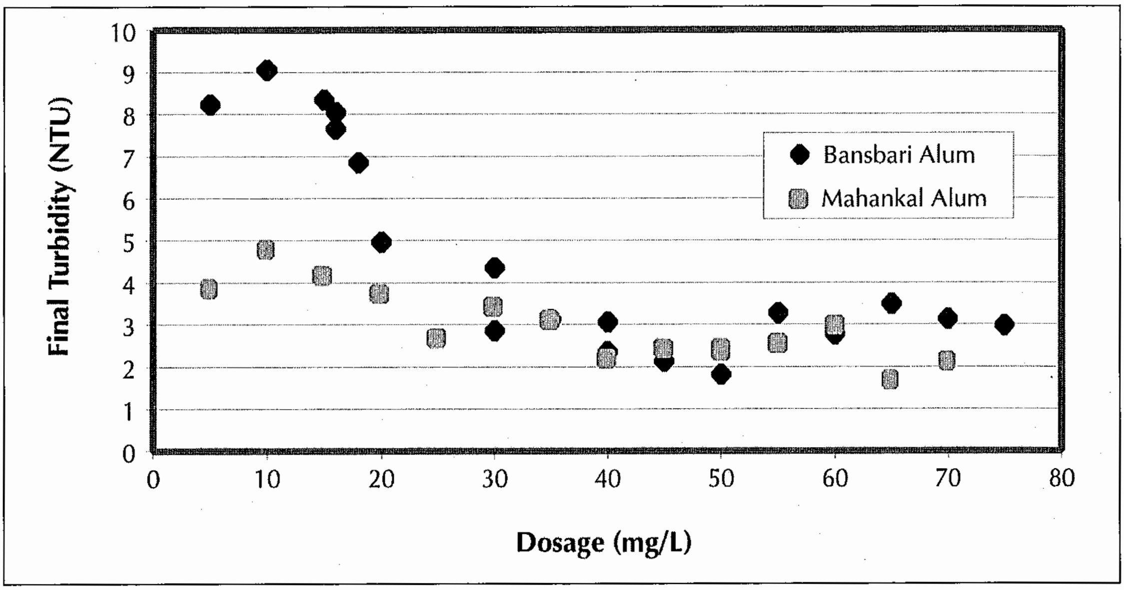

FIGURE 12. Final turbidity versus alum dosage.

and Mahankal treatment plants. Of the two local alum products, Bansbari alum yielded the best results. Analyses using raw water samples with Bansbari alum showed effective removal results for dosages greater or equal to 35 mg/L. Raw samples were chemically untreated water that had not undergone any type of mixing and settling. Dosages less than this value were ineffective in removing turbidity. Dosages between 35 and 75 mg/L achieved turbidity removal efficiencies between 64 and 81 percent. The final turbidity values at these doses ranged between 1.89 and 3.49 NTU, well below the WHO guideline of 5 NTU. Doses greater than 75 mg/L did not produce better removal efficiencies.

Analyses using raw water samples with Mahankal alum produced turbidity removal values ranging between 47 and 51 percent at dosages between 40 to 50 mg/L. As the alum

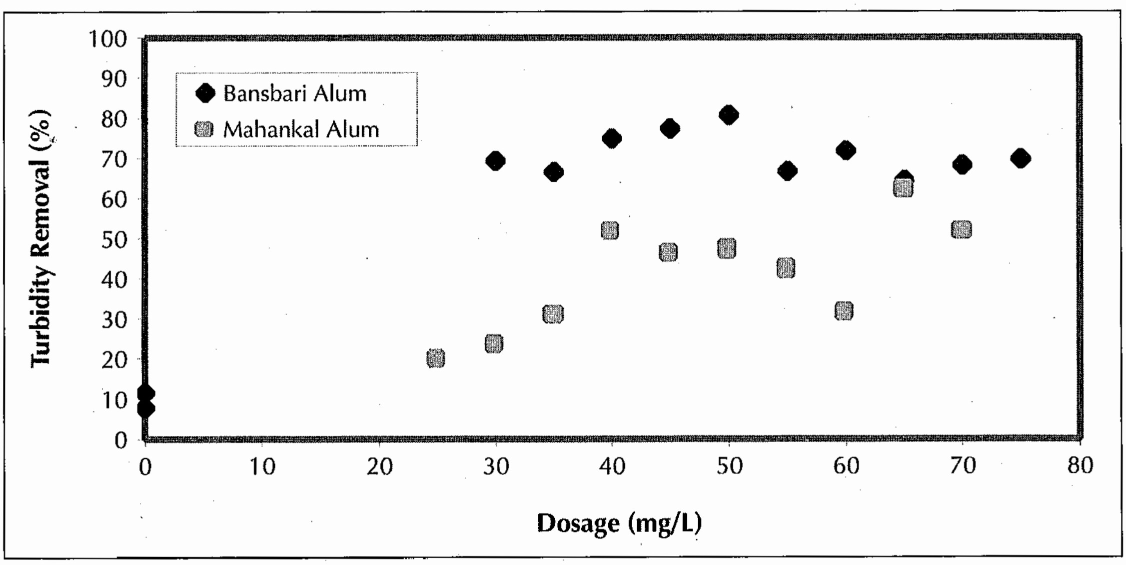

FIGURE 13. Turbidity removal efficiencies versus alum dosage.

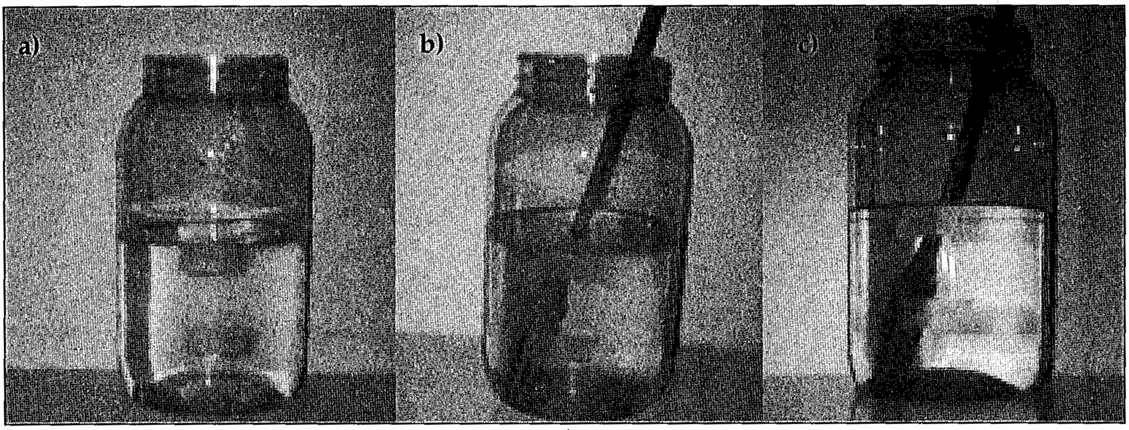

FIGURE 14. Manual coagulation and settling experiment — a) raw water, b) at start of settling time and c) after 30 minutes of settling.

dosage increased above 40 mg/L, the efficiency of removal decreased. Optimum final turbidity values ranged between 2.2 to 2.5 NTU. Final turbidity and turbidity removal efficiencies are shown in Figures 12 and 13, respectively.

The rate of mixing during the coagulation and flocculation phase of POU treatment was extremely important. Excessive stirring resulted in an increased susceptibility of floc breakup. Initial experiments in which water was shaken instead of stirred yielded poor flocculation results. To make manual coagulation resemble laboratory jar-stirring, a utensil with a paddle-like tip should be used during mixing to ensure good interparticle contact. The direction of stirring should be consistently and gently changed so that the water is not simply being moved around as one unit volume.

In the manual coagulation experiments, after 15 minutes of settling, the size of floc particles was approximately 2 millimeters (mm). After 30 minutes, floc particles reached a size of 4 mm and a layer of settled floc particles formed on the bottom of the container. Noticeable color reduction was observed (see Figure 14). After a full hour of settling, more floc particles settled out of the system, but some color remained.

Translating recommended dosages into quantities measurable by the Nepalese people is crucial to the success of POU coagulation. Solutions and dosages were measured in terms of locally available plastic drinking water bottles. The cap of the bottle can be used for measuring the coagulant and the bottle itself can hold the dissolved coagulant solution. In order to achieve a 40 mg/L dose, one capful of 2 percent coagulant solution should be used for every 2 liters of water to be treated. The 2 percent solution can be made by adding two level capfuls of ground alum to 500 mL of clean water, the equivalent of one small water bottle commonly available in shops in Nepal.

POU coagulation is a feasible option for the pretreatment of Nepalese drinking water. Compared to the Indian or the Haitian filters, costs of the drinking water bottles and alum are minimal (alum costs $0.50 for 100 grams in the shops in Kathmandu, a mortar and pestle costs $5.00 and a plastic water bottle costs $0.25, for a total of $5.75); therefore; it is an economically viable means of effectively reducing, but not eliminating, turbidity and color from raw water. Also, alum is commonly available in marketplaces in Nepal. However, informally polled villagers in the Kavre District revealed that manual coagulation was too much work for women all ready overburdened with household and agricultural work and filtration would be the preferred means of particle removal.

Filtration. Three filter/purifier systems were studied as possible drinking water treatment options for Nepalese households. The systems considered were an Indian ceramic candle filter (see Figure 15), a Nepalese ceramic candle filter (see Figure 16) and a Haitian purifier (see Figure 17).

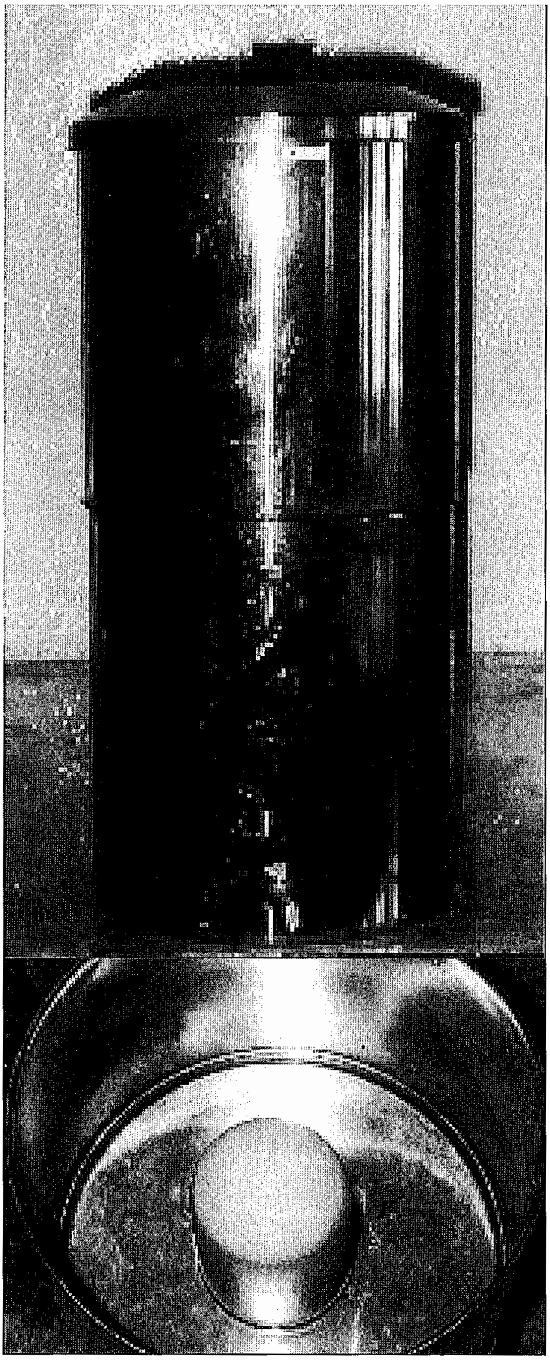

FIGURE 15. Indian ceramic candle filter.

Indian ceramic candle filters are commonly used household filtration systems in Nepal among the middle- and upper-income groups. The system consists of two stainless steel containers. The top container holds the ceramic candle filter and the untreated water. The bottom container stores and dispenses treated water through a spigot.

The locally manufactured ceramic candle filter is much less expensive than the Indian ceramic candle filter, yet its use is not widespread. Nepalese ceramic candle filters are similar in design to those manufactured in India. However, since these filters are handmade in a small workshop, the supply is limited.

The Haitian purifier consists of two filters: a string-wound sediment filter and an activated carbon filter. The string-wound filter removes particulates and microbes and the activated carbon filter removes unwanted chemicals such as chlorine, heavy metals and pesticides. This unit requires chlorine disinfection prior to filtration because the activated carbon filter is susceptible to bacterial growth within the filter.

Test results indicated that all three filter systems removed turbidity to levels below the WHO limit of 5 NTU. As shown in Figure 18, the average raw water turbidity level was 12.3 NTU and the average turbidity of treated water was below 1 NTU for each filter.

Raw water used in all filtration runs tested positive for total coliform and *E. coli*. After treatment through the filtration units, P/A tests showed mixed results, as summarized in Table 3. Water treated by the Haitian purifier removed both *E. coli* and total coliform when 20 ppm of chlorine was added as a disinfectant. However, the purifier did not remove *E. coli* or total coliform without the addition of chlorine. The Indian ceramic candle filter removed *E. coli* but showed the presence of total coliform after treatment. The Nepalese ceramic candle filter showed the presence of both total coliform and *E. coli* contamination after treatment.

With the five-tube MPN method, using the Haitian purifier and adding chlorine was found to remove hydrogen-sulfide–producing bacteria to levels less than the lowest detection limit of 1.1 bacteria per 100 mL of water. Between the two ceramic filters, five-tube MPN tests indicated that the Indian ceramic filter removed hydrogen-sulfide–producing bacteria better than the Nepalese ceramic filter (1.6 MPN bacteria per 100 mL versus 3.9 MPN bacteria per 100 mL in treated water). However, in

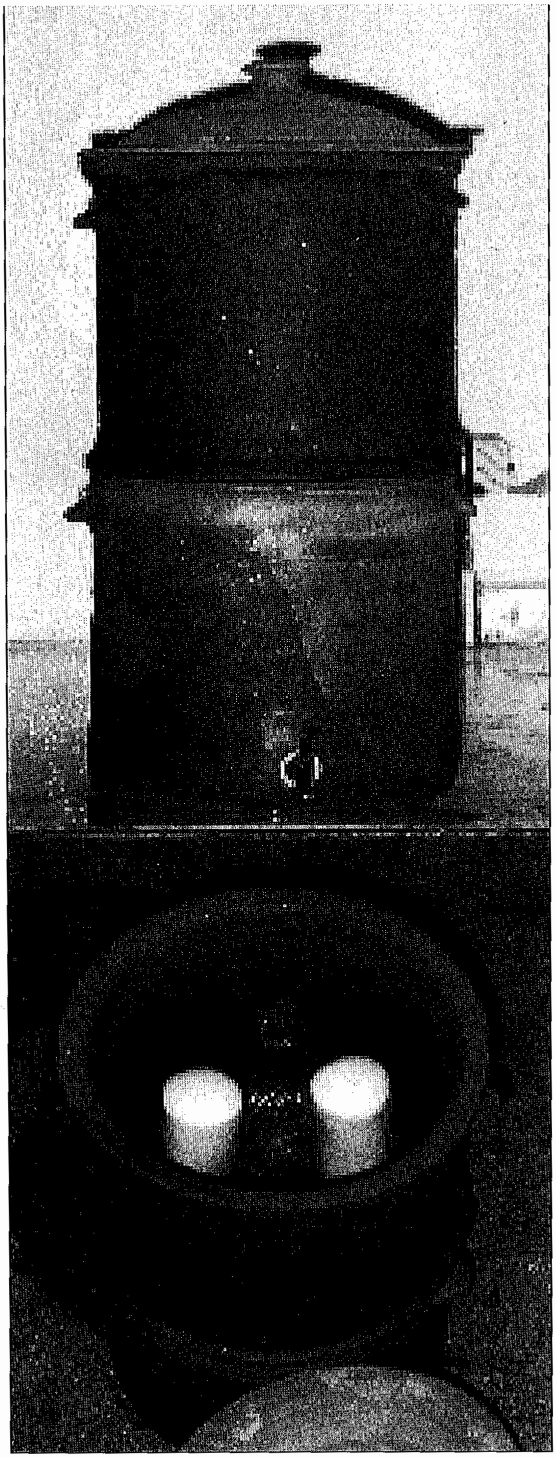

FIGURE 16. Nepalese ceramic candle filter.

summary, neither of the ceramic filters produced water free from total coliform, *E. coli* or hydrogen sulfide contamination.

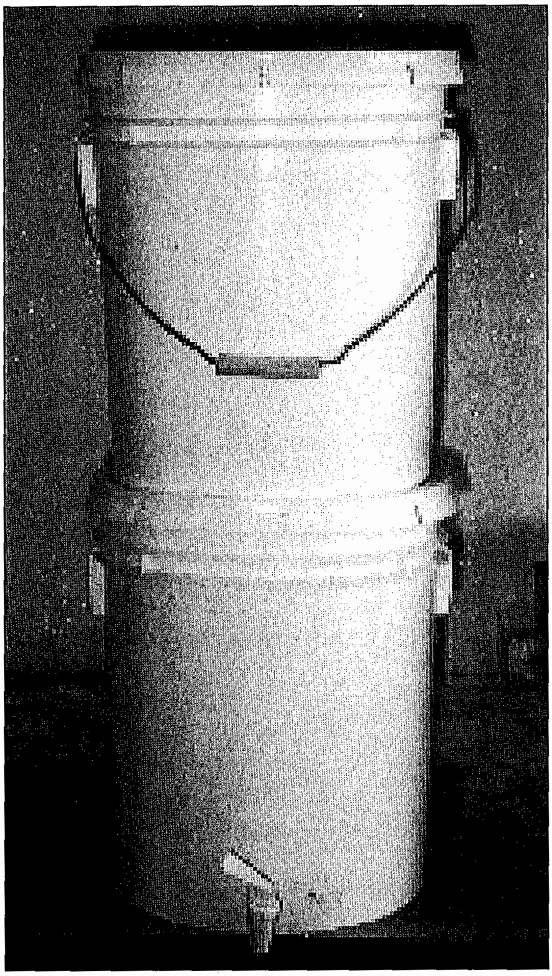

FIGURE 17. Haitian purifier.

In the filtration study, test results indicated that none of the three filtration units were adequate in treating water to an acceptable quality. The Nepalese ceramic candle filter remains the most affordable filter of all the systems tested ($3 for the Nepalese filter versus $9 to $23 for the Indian filter, depending on volume, and $15 for the Haitian filter). Although the Nepalese filter does not remove pathogenic organisms, it is an effective method of removing turbidity. Filtration using any of these three filters needs to be combined with disinfection in order to produce safe drinking water.

Solar Disinfection. Solar disinfection uses infrared heat and ultraviolet radiation (UVR) from solar energy to disinfect water. The simplest application of this technique is the batch

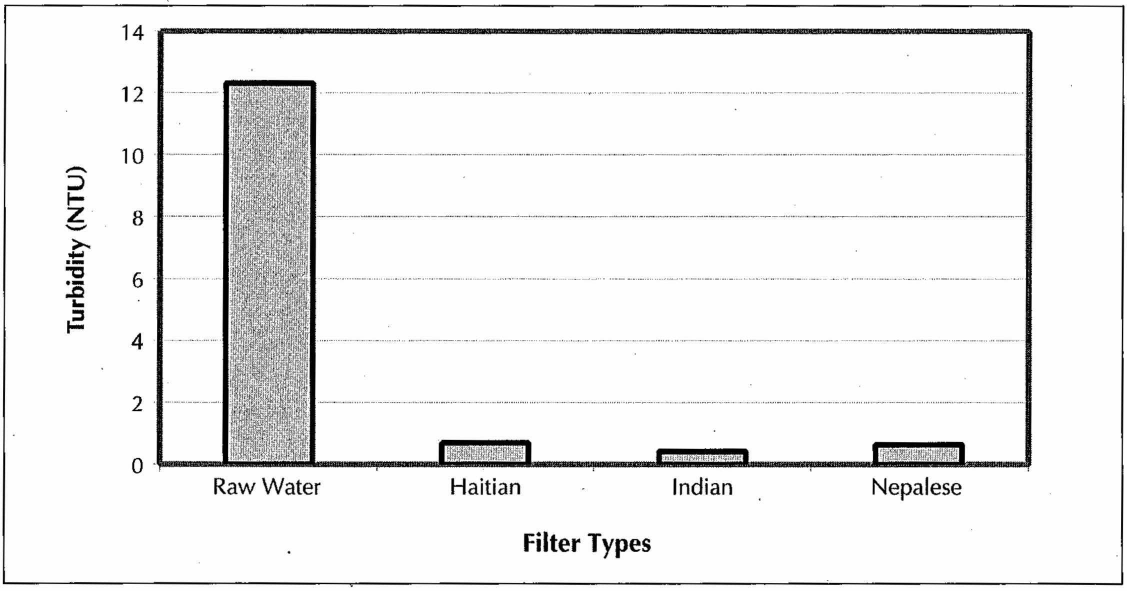

FIGURE 18. Turbidity removal of the filter systems.

model in which small volumes of water (less than 3 liters) are exposed to the sun in transparent containers. This technique is highly dependent on the availability and quantity of solar energy and the clarity of the water being treated.

Bacterial and viral inactivation is possible through both optical and thermal mechanisms. Ultraviolet-A (UV-A) radiation is responsible for optical inactivation of microorganisms.[15] Inactivation causes strand breakage and base changes in DNA. Strand breakage is usually lethal, while base changes block replication and produce other mutagenic effects.[16] Although there has been no significant correlation observed between mean water temperature and bacterial survival in the range of 5 to 37°C, thermal inactivation remains an important part of the solar disinfection process. There is strong evidence of a synergetic heat effect on solar disinfection when water temperatures are above 45°C.[17] Thermal pasteurization is the primary means of disinfection at temperatures exceeding 65°C.[18] Although it is difficult to heat water to 65°C using batch type solar disinfection, temperatures around 45°C are certainly possible in Nepal, but not in Kathmandu during the coldest month of January.

TABLE 3.
P/A Test Results After Filtration

Filter Type	Total Coliform	*E. Coli*
Haitian Purifier (with Chlorine)	–	–
Haitian Purifier (without Chlorine)	+	+
Indian Ceramic Filter	+	–
Nepalese Ceramic Filter	+	+

A number of factors affect the intensity and duration of solar radiation in Nepal. These factors include latitude, geographic location, pollution level, time of year and meteorological conditions. Mean daily solar radiation ranges between 3,800 watt-hours per square meter per day (Wh/m^2/day) in January to greater than 7,000 Wh/m^2/day in May.[19,20] The relatively clear skies during the winter months are counterbalanced by fewer hours of available sunlight. Conversely, the cloud cover of the monsoon offsets the increased solar radiation associated with longer days in the summer months. At the altitudes in the Kathmandu Valley the intensity of UVR is significantly greater than at sea level. However, air pollution over Kathmandu robs solar radiation of a significant portion of its ultraviolet light. Because of all these factors, it was difficult to conclude from the January 2000 field study in Nepal whether this region will be suitable for year-round solar disinfection.

Previous studies conducted in the Terai lowlands of Nepal determined that the removal of indicator organisms by solar disinfection in direct sunlight required 4,700 Wh/m^2 (5 or 6 hours of exposure during the peak sunlight hours).[21] The same study reported that using a blackened rack reduces the requirement to 3,000 Wh/m^2 (3 to 4 hours of peak sunlight) and a solar reflector reduces it further to 1,000 Wh/m^2 (approximately 1 hour of peak sunlight). However, it is important to note that these studies were conducted in the months of April and May in the Terai region in which the climate and meteorological conditions are optimal, with average daily insolation values above 6,500 $Wh/m^2/day$.

In order to maximize disinfection effectiveness, it is essential to minimize solar transmission losses through the water container. These losses depend on the optical properties of the container. The plastic and glass bottles used in this study have transmission ratios shown in Table 4.

TABLE 4.
Solar Disinfection Container Transmission Percentages

Bottle Type	Transmittance (%)
Transparent Glass	73
Transparent Plastic	88
Blue Transparent Plastic	87

Solar radiation passing through water is further attenuated by turbidity. The commonly recommended turbidity threshold for water undergoing solar disinfection is 30 NTU. Turbidities above 200 NTU can absorb as much as 99 percent of the incident radiation within the first centimeter of optical path.[22] Optical inactivation is significantly retarded under these highly turbid conditions. Turbidity in the sample water tested during January 2000 in Kathmandu averaged 8 to 12 NTU.

Clear and half-blackened bottles were used to measure the solar heating effect. Figure 19 summarizes the sample temperature at various times during an average January day in Kathmandu. A slight increase in temperature was observed in the half-blackened bottles. However, the temperature did not approach the threshold temperature of 45°C required for thermal inactivation. Thus, disinfection occurred only due to UVR.

In the first round of tests, unfiltered water samples were subjected to 4 hours of exposure time and showed removal of hydrogen-sulfide–producing bacteria in all trials. However, removal of total coliform and *E. coli* varied widely from test to test. In a second round of tests, water filtered in one of the three different filters — Indian, Nepali or Haitian — was exposed to 4 hours of radiation. For the water treated by the Indian filter and exposed to 4 hours of radiation, all three indicator tests for total coliform, *E. coli* and hydrogen-sulfide–producing bacteria were negative. The Nepali ceramic candle filtered water exposed to 4 hours of solar radiation showed the absence of *E. coli* and hydrogen-sulfide–producing bacteria, but the presence of total coliform. The Haitian filtered and chlorinated water, exposed to 4 hours of radiation, experienced no detectable change in microbial quality after solar treatment.

The third round of tests extended the exposure period of unfiltered water sample to two consecutive days (approximately 11 hours). These results were the most promising of all trials performed. Total coliform was absent in nine of 12 tested samples. *E. coli* was absent in 12 out of 12 tested samples. Hydrogen-sulfide–producing bacteria tests were not performed in this trial.

The results of the solar disinfection study suggested that filtration prior to solar treatment and/or two consecutive days (11 hours) of solar treatment were necessary to safely treat raw water for bacterial contamination when turbidity was in the range of 8 to 12 NTU in Kathmandu during January (the coldest season).

Conclusion

Water quality studies found that most drink-

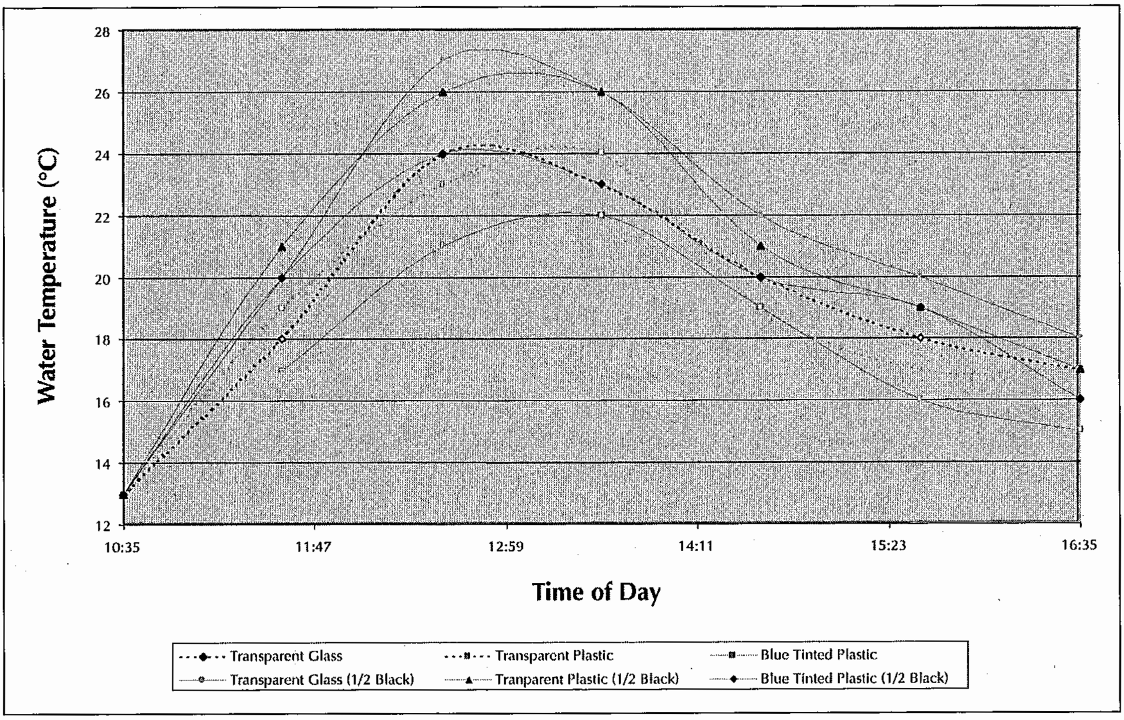

FIGURE 19. Water temperature versus time of day.

ing water supplies in the Kathmandu Valley were microbially contaminated based on tests using the indicator organisms: total coliform, *E. coli* and/or hydrogen-sulfide–producing bacteria. Well water, stream water, treatment plant distribution pipe water and consumption point water showed contaminant presence ranging from 50 to 100 percent of the samples tested. Arsenic contamination was not found in Kathmandu Valley, but was above WHO guidelines in 18 percent of tube wells tested in the Terai; and nitrates were found mostly in urban shallow tube wells, while ammonia was found in the Kathmandu Valley's deep boring wells. To treat the widespread microbial contamination of Nepal's drinking water supply a multifaceted POU treatment regime is recommended. Specifically, drinking water should undergo filtration to remove turbidity, followed by an effective disinfection process to inactivate microbes. A two-step, POU treatment system consisting of a Nepalese ceramic candle filter followed by either solar or chlorine disinfection offers a possible alternative drinking water treatment regimen for Nepalese households. Alternatively, raw water with a moderate turbidity concentration (8 to 12 NTU) may be exposed to two days of solar radiation to achieve disinfection during the coldest month of the year (January). The choice of chlorine or solar disinfection depends on the availability of chemical supplies or solar radiation.

NOTES & ACKNOWLEDGMENTS — *This article describes the first Nepal Water Project, conducted over the course of the 1999–2000 academic year at the Massachusetts Institute of Technology (MIT) in Cambridge, Massachusetts, and in the Terai and Hill regions of Nepal. The objectives of the first year of the project were to assess the water quality of selected urban and rural locations in Nepal and to recommend point-of-use (POU) treatment methods to decrease the incidence of waterborne illnesses. Seven graduate students from MIT and their advisor, Susan Murcott, Lecturer in the Department of Civil and Environmental Engineering (CEE), spent three weeks in Nepal in January 2000 collecting and analyzing samples, evaluating water treatment methods and investigating the water supply sys-*

tem and water culture in Nepal. The participants undertook this project as part of the Master of Engineering Program in MIT's CEE Department. The group was hosted by the Nepal Department of Water Supply and Sewerage, the Nepal Water Supply Corporation, UNICEF–Nepal and the Federation of Business and Professional Women–Nepal. Special support and assistance was provided by Mangala Karanjit. The John R. Freeman Fund, administered through the Boston Society for Civil Engineers Section/ASCE, generously sponsored this project. The MIT CEE Department, Master of Engineering Program, under the Direction of Dr. Eric Adams, provided the remainder of the financial support for the Nepal Project. The authors would like to thank Kipp and Zonen, Phipps and Bird Co., and Spectronics Instruments for donating the equipment that made this study possible. Turbidity was measured using a 2100P Portable HACH Turbidimeter. EM Quant test strips and Affiniti Concentration kits were used to analyze arsenic concentrations in the drinking water samples. Drinking water samples were analyzed using two spectrophotometers: the Spectronics 20 Genesys spectrophotometer loaned to the project by Spectronics Instruments and the HACH DR/2010 spectrophotometer. Solar intensity was logged hourly using a SOLRAD CM3/CC20 solar pyranometer/datalogger loaned to the MIT team by Kipp and Zonen. One of the three filter/purifier systems studied as possible drinking water treatment options for Nepalese households, the Haitian purifier, was developed by the U.S. non-governmental organization, Gift of Water, Inc. Madhyapur Clay Crafts manufactures the Nepalese ceramic candle filters. Coagulation and settling experiments were performed at the Nepal Water Supply Corporation's Central Laboratory using a mechanized flocculator donated to the MIT team by the Phipps & Bird Company. Peter Moulton, of Global Resources Institute, conducted an independent field trial of solar disinfection tests in the Terai region and helped advise the team. Dr. Lee Hersh and his son, Cliff Hersh, accompanied the team and assisted the project in numerous ways. Andy Bittner, Amer M.A. Khayyat, Kim Luu, Benoit Maag, Patricia M. Pinto, Junko Sagara and Andrea Wolfe received their Master of Engineering degrees in Civil and Environmental Engineering from MIT in June 2000.

ANDY BITTNER *graduated Cum Laude from the University of Michigan in 1997 with a Bachelor of Science and Engineering degree in Civil and Environmental Engineering and a Bachelor of Science in Physics. He currently works for Gradient Corporation on issues related to groundwater modeling and contaminant fate and transport.*

AMER M.A. KHAYYAT *graduated from Brown University with a Bachelor of Science degree in Mechanical Engineering in 1999. He works for Schlumberger Reservoir Evaluation in Doha, Qatar, as a senior field engineer.*

KIM LUU *graduated cum laude in 1999 from University of California, Los Angeles, with a Bachelor of Science degree in Civil and Environmental Engineering. She currently works for Environ International Corporation in Irvine, California.*

BENOIT MAAG *received a Bachelor of Science degree from the École Polytechnique in 1985 and a Master of Science degree from the National Engineering School for Advanced Technology in 1987. He worked in Tokyo, Japan, from 1997 to 1999 for Saint-Gobain Quartz. He currently works for Saint-Gobain Quartz at its California headquarters.*

SUSAN E. MURCOTT *is a Lecturer in the Department of Civil and Environmental Engineering at the Massachusetts Institute of Technology (MIT). She is also the supervisor of the MIT Nepal Water Project. She received bachelor and master's degrees in Civil and Environmental Engineering from MIT in 1990 and 1992, respectively. She also maintains a consulting practice with her company, Ecosystems Engineering.*

PATRICIA M. PINTO *graduated with distinction from Cornell University with a Bachelor of Science degree in Agricultural and Biological Engineering degree in 1996. She worked for the U.S. Army Corps of Engineers as a project engineer in New York, New York, from 1996 to*

1999. She currently works for Sanborn, Head & Associates, Inc., as a project engineer.

JUNKO SAGARA *graduated in 1999 from McGill University with a Bachelor of Engineering degree in Civil Engineering. She currently works for Camp Dresser and McKee, Inc., in Osaka, Japan.*

ANDREA WOLFE *graduated from Swathmore College with a Bachelor of Science in Engineering degree in 1999. She currently works for Fall Creek Engineering in California.*

REFERENCES

1. Adhikari, A., "Environmental Problems in the Kathmandu Valley," in *Urban and Environmental Planning in Nepal,* IUCN, The World Conservation Union, 1998.

2. *www.undp.org,* 2001.

3. United Nations Development Program, *Nepal Human Development Report 1998,* New York, 1998.

4. World Health Organization, *Guidelines for Drinking-Water Quality,* second edition, Vol. 2, Geneva, Switzerland, 1996.

5. From the World Health Organization web site: *www.who.int/water_sanitation_health/GDWQ/Summary_tables/Tab1.htm.*

6. Fujioka, R., "Appropriate Hygenic Water Quality Standards for Tropical Pacific Islands," in *Proceedings of the Eighth Pacific Islands Area Seminar,* December 1-4, 1997, Takai University, Honolulu, Hawaii.

7. Khayyat, A., *Study of Point of Use Water Disinfection Methods for the Treatment of Drinking Water in Nepal,* master's thesis, Massachusetts Institute of Technology, Cambridge, Mass., May 2000.

8. Bottino, A., Thapa, A., Scatolini, A., Ferino, B., Sharma, S., & Pradhananga, T.M., "Pollution in the Water Supply System of Kathmandu City," *Journal of the Nepal Chemical Society,* Kathmandu, Nepal, 1991.

9. Shrestha, R.R., & Sharma, S., *Bacteriological Quality of Drinking Water in Kathmandu City: A Review of ENPHO/DISVI Reports, 1988–1992,* Environment and Public Health Organization, Kathmandu, Nepal, 1995.

10. U.N. Children's Fund, "Nepal," *www.unicef.org/statis/Country_1Page123.html,* April 27, 2000.

11. U.S. Agency for International Development, "USAID Assistance for Nepal," *www.info.usaid.gov/country/ANE/nepal.html,* April 21, 2000.

12. Morganti, L., *Chlorine Generation in Nepal,* master's thesis, Massachusetts Institute of Technology, Cambridge, Mass., May 2002.

13. Acra, A., Jurdi, M., Mu'allem, H., Karahagopian, Y., & Raffoul, Z., *Water Disinfection by Solar Radiation: Assessment and Application,* Ottawa, Ontario, Canada, International Development Research Centre, 1990.

14. Swiss Federal Institute for Environment and Technology, EAWAG/SANDEC, *www.sodis.ch.*

15. McGuigan, K.G., Joyce, T.M., Conroy, R.M., Gillespie, J.B., & Elmore-Meegan, M., "Solar Disinfection of Drinking Water Contained in Transparent Plastic Bottles: Characterizing the Bacterial Inactivation Process," *Journal of Applied Microbiology,* Vol. 84, No. 6, June 1998.

16. McGuigan, K.G., Joyce, T.M., & Conroy, R.M., "Solar Disinfection: Use of Sunlight to Decontaminate Drinking Water in Developing Countries," *Journal of Med. Microbiology,* Vol. 48, No. 9, September 1999.

17. Wegelin, M., Canonica, S., Mechsner, K., Pesaro, F., & Metzler, A., "Solar Water Disinfection: Scope of the Process and Analysis of Radiation Experiments," *Journal of Water SRT-Aqua,* Vol. 43, No. 3, 1994.

18. Andreatta, D., Yegian, D.T., Connelly, L., & Metcalf, R.H., "Recent Advances in Devices for the Heat Pasteurization of Drinking Water in the Developing World," in *Proceedings of the 29th Intersociety Energy Conversion Engineering Conference,* American Institute of Aeronautics and Astronautics, 1994.

19. Mani, A., & Randgarajan, S., *Solar Radiation Over India,* New Delhi, India, Allied Publishers Private, Ltd., 1982.

20. Smith, M.K., *Microbial Contamination and Removal from Drinking Water in the Terai Region of Nepal,* master's thesis, Massachusetts Institute of Technology, Cambridge, Mass., June 2001.

21. Global Resources Institute, *www.grilink.org/water1.htm.*

22. Joyce, T.M., McGuigan, K.G., Elmore-Meegan. M., & Conroy, R.M., "Inactivation of Fecal Bacteria in Drinking Water by Solar Heating," *Appl. Environ. Microbiol.,* Vol. 62, No. 2, February 1996.