Environ. Sci. Technol. **2004**, *38,* 6783−6789

Testing Groundwater for Arsenic in Bangladesh before Installing a Well

A. VAN GEEN,* T. PROTUS, Z. CHENG, AND A. HORNEMAN

Lamont-Doherty Earth Observatory of Columbia University, Route 9W, Palisades, New York 10964

A. A. SEDDIQUE, M. A. HOQUE AND K. M. AHMED

Geology Department, University of Dhaka, Dhaka, Bangladesh

Profiles of groundwater and sediment properties were collected at three sites in Bangladesh with an inexpensive sampling device that is deployed by modifying the local manual drilling method. Dissolved As concentrations in the groundwater samples ranging from 5 to 600 μg/L between 5 and 50 m depth closely matched vertical profiles from nearby nests of monitoring wells. In combination with a field kit, the device provides a means of targeting aquifers for the installation of tube wells that meet the drinking water standard for As. The device is also a useful research tool for unraveling the relationships between the As content of groundwater and the complex structure of flood plain and deltaic environments throughout South Asia.

Introduction

A compilation of the latest estimates suggests that probably over 100 million rural inhabitants of Bangladesh, West Bengal (India), Vietnam, China, and several other South Asian countries routinely consume groundwater containing over 10 μg/L As, the guideline value for drinking water set by the World Health Organization (*1*−*4*). Because most of the existing wells are less than 10 years old and the lesions and cancers resulting from arsenic exposure can take decades to develop, the proportion of the population that is visibly affected by arsenicosis is presently relatively small (*5*−*7*). Cancer deaths in Bangladesh may double in the next decades as a result of past exposure to arsenic in groundwater, however (*8*). In addition, a significant impact on the mental development of children due to As exposure in Bangladesh was recently demonstrated (*9*).

The sheer scale of the problem is one of the reasons mitigation efforts conducted by various governments with support from international and nongovernmental organizations over the past decade have hitherto not been very successful. In Bangladesh alone, there are over 10 million tube wells, most are privately owned, and the As content of groundwater pumped from approximately half these wells exceeds 10 μg/L (*3*). One-third of these wells do not meet the Bangladesh national standard for As in drinking water of 50 μg/L either. Broad patterns in the severity of the problem throughout the country have been identified, but these cannot be used to predict the status of a particular well because of the highly mixed distribution of safe and unsafe wells (*3*, *10*). Mitigation efforts have therefore focused largely on blanket testing of wells with field kits throughout the most affected parts of the country.

The premise of this contribution is that even though the As content of groundwater in Bangladesh has caused and will continue to cause considerable pain and suffering, groundwater remains the most viable mitigation option for the foreseeable future. Calls for a return to surface water have to date not been matched by the provision of options viable at the village scale for removing human pathogens from pond or river water (*11*). The alternative of removing arsenic from groundwater is logistically complex and has met with little success beyond the pilot level (*11*). In our opinion, the most promising ways of reducing the exposure of the Bangladesh population therefore remain the sharing of existing wells that are low in As (*12*) and the targeting of those aquifers low in As for the installation of additional safe wells (*10*, *13*).

This paper describes a simple groundwater and sediment sampling device that has successfully been deployed by local drilling teams in Bangladesh. With minor modifications and in combination with the widely used Hach kit, the needle-sampler could allow teams of drillers in many parts of the country to test an aquifer before installing a well. The aquifer could also be tested in the field in advance for Mn, which is known to frequently exceed its WHO guideline of 0.5 mg/L in Bangladesh (*3*, *14*). A significant benefit from prior testing with the needle-sampler is that it reduces the waste of resources on a well that turns out to be unsafe.

The reliability of the needle-sampler is demonstrated here by comparing detailed groundwater concentration profiles of As collected with the needle-sampler at three locations with the composition of groundwater from nearby nests of monitoring wells. Additional results for the major cations Na, K, Mg, and Ca and the redox-sensitive elements Fe, Mn, S, and P as well as the Fe(II)/Fe ratio of the acid-leachable Fe fraction of the sediment show that the needle-sampler is also a useful research tool for investigating the underlying causes of the bewildering distribution of groundwater As in deltaic and flood plain environments.

Materials and Methods

Geological Setting. The needle-sampler was tested in three villages of Araihazar upazila that span much of the spectrum of conditions in the ~86 000 villages of Bangladesh. The vertical distribution of groundwater As in the same three villages has previously been described (*10*, *15*, *16*). The concentration of other elements of health concern, Mn in particular, in a subset of groundwater samples from Araihazar is discussed by Cheng et al. (*14*). Site A is located in the center of Dari Satyabandi village (23.785 °N, 90.603 °E) where approximately half of the existing wells supply groundwater containing less than 50 μg/L As. At Site B in Baylakandi village (23.780 °N, 90.640 °E), in contrast, very few wells meet the Bangladesh standard for As. Finally in Lashkardi village (23.774 °N, 90.606 °E), nearly all existing wells surrounding Site F supply water containing less than 50 μg/L As. The three villages are only a few kilometers apart. This level of spatial variability from one neighboring village to the other is likely to extend over many parts of the country (*3*, *7*, *10*).

Deployment of the Needle-Sampler. The needle-sampler consists of three main components: (1) a clear PVC sample chamber capped with a silicone stopper to collect groundwater and sediment, (2) a needle and plunger assembly to transfer groundwater and sediment from a depth slightly greater than that of the drill hole to the sample chamber, and (3) a housing unit that connects the needle and plunger

* Corresponding author phone: (845)365-8644; fax: (845)365-8154; e-mail: avangeen@ldeo.columbia.edu.

10.1021/es049323b CCC: $27.50
Published on Web 10/22/2004

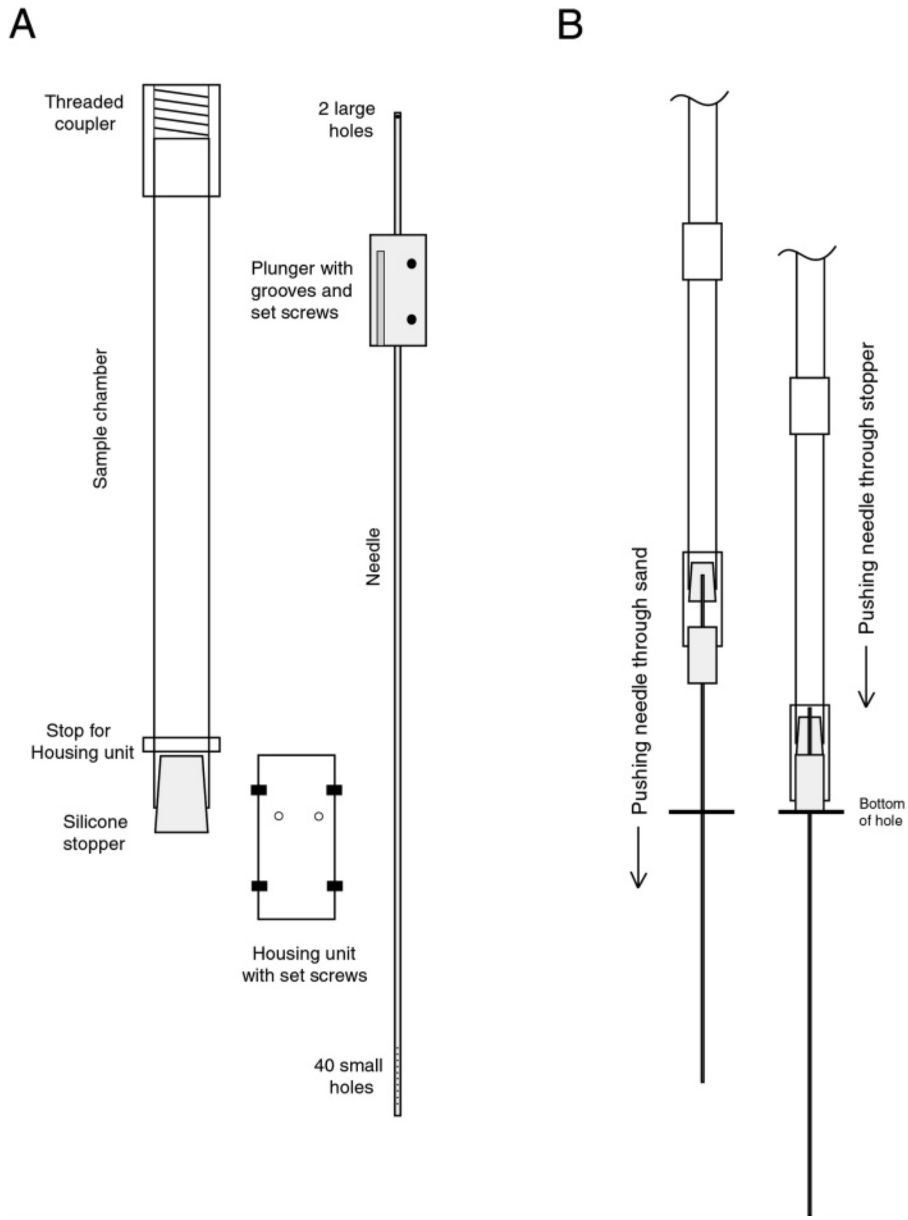


FIGURE 1. (A) Schematic showing the three main components of the needle-sampler and (B) the two stages of deployment.

assembly to the sample chamber (Figure 1A). If aquifer material is collected from more than one depth, sample chambers can be replaced between successive deployments to allow processing without unnecessarily slowing down the drilling. The needle-plunger assembly and the housing are typically reused between deployments.

The needle-sampler is deployed by first drilling to the targeted depth using the entirely manual method that has been used to install the vast majority of the millions of wells in Bangladesh. The so-called "sludger" or "hand-flapper" method relies on 15 ft sections of "$1^1/_2$″ Schedule 20" gray PVC pipe connected by threaded metal couplers to rhythmically clear a hole by recirculating water, using the hand as a check-valve (*15, 17*). The dimension of the PVC pipe refers to its inner diameter. Imperial units, widely used also in Bangladesh, are provided because the device was constructed with industrial materials defined in these units. Although no rotation is actually involved, we follow local custom by referring to the process as "drilling" and to the sediment suspended in the recirculating water as "cuttings". Depending on the thickness of clay layers that are encountered, the method allows a team of 3−4 men to drill through ∼300 ft (90 m) of unconsolidated deltaic or flood plain sediment within a day.

Before deployment, the sampling tube is evacuated to ∼0.1 atm by passing a 2″-long 16-gauge septum-piercing needle (Hamilton Co. "Pt Style 5", Cat. No. 90216) through the silicone stopper and connecting it to a Nalgene hand-pump (Fisher Scientific Cat No. 13-874-614A). After swiftly removing the needle to avoid a loss of vacuum, the sampling needle, in combination with the plunger and housing, is pushed through the same centered hole mid-way through the silicone stopper (Figure 1B). The unit is ready for deployment after the set screws of the housing are tightened onto the tube. The other two set screws on the housing that guide the plunger rarely need to be readjusted.

The needle-sampler is lowered into the drill hole within the ∼1.5″ ID drill pipe by threading it onto successive 10 ft (3 m) sections of thinner "$^3/_4$″ Schedule 20" PVC pipe (Figure 1B). The thin pipe section directly above the needle-sampler is drilled with a few dozen $^1/_4$″ holes to allow water to pass. When the bottom of the drill hole is reached, the string of pipes to which the needle-sampler is attached is gently rotated clockwise and pushed so the needle penetrates the sandy sediment without causing the plunger to slide (Figure 1B). The string of thinner drill-pipe is then pushed more forcefully for the plunger to slide and the tip of the needle to clear the silicone stopper inside the sampling tube. At this stage, the evacuated tube rapidly fills almost entirely with groundwater as well as some sediment. After retrieving the needle-sampler by withdrawing the inner sections of PVC pipe, two set screws are loosened to separate the sampling tube with its silicone stopper from the needle.

Construction of the Needle-Sampler. The sample chamber deployed at Sites A and B in October 2003 consists of a 12″ section of clear "$^3/_4$″ Schedule 40" PVC pipe (Figure 1A). Technical drawings of all the components of the needle-sampler are provided with the Supporting Information. One end of the pipe is covered with a glued 1″ OD clear PVC disk that is capped with a clear PVC $^3/_4$″ NPT female-$^3/_4$″ socket adapter. A split PVC ring made from 1″ clear PVC pipe is glued ~1″ from the open top of the tube. The open end of the tube is closed with a U.S. size No. 3 silicone stopper (Fisher Scientific Cat. No. 09-704-1H).

The 18″-inch long custom needle is made of 10-gauge stainless steel, closed, and rounded at both ends (Hamilton Co., Cat No. 01644066). The sides of the needle are drilled with two ~5/64″ mm diameter holes at one end and a series of forty 0.031″ diameter holes at the other end. A few of the smaller holes have occasionally been enlarged to collect a larger amount of sediment. The needle passes through a 3.5 mm diameter hole at the center of a 1.030″ OD stock PVC plunger and is kept in place by a set of 4 set screws (1/4−20 × 3/8″ cup point, stainless steel). The plunger also has two 0.25″-wide, 1.6″-long, rounded slots along the side.

The third component of the needle-sampler, the plunger housing, connects the plunger-needle combination to the upper part of the body of the sampling tube with two $^1/_4$-20 × 3/16″ set screws (Figure 1A). A second pair of $^1/_4$-20 × 3/16″ set screws at the other end of the housing extends into the two slots along the side of the plunger to prevent it from detaching itself from the sample tube and falling into the drill hole. The position of the piston on the needle is adjusted so one end of the needle entirely pierces the silicone stopper when the piston is nearly flush with the outer end of the sleeve (Figure 1B).

The earlier version of the needle-sampler deployed at Site F in October 2002 was somewhat different, although based on the same principle. The wider diameter of this prototype was identical to that of the drill pipe ("1$^1/_2$″ Schedule 20" gray PVC). Groundwater was aspirated through a similar combination of needle and plunger into a 100 mL centrifuge tube capped with a silicone stopper and placed within the body of the sampler. The larger needle-sampler was deployed at the end of the standard drill string, which therefore had to be entirely disassembled between deployments. In addition to the savings in time, the thinner version was designed to reduce the chance of the hole collapsing while the drill pipe is removed.

Water and Sediment Analyses. For analysis of dissolved constituents, groundwater inside the sampling tube was filtered in the field in two ways. For all samples, the silicone stopper was first pierced with two septum piercing 16-gauge stainless steel needles, 2″ and 8″-long, respectively (both Hamilton Co. "Pt Style 5"). A 0.45 μm syringe filter (Pall Gelman IC Acrodisk No. 4585) was attached to the longer needle, and the tube was gently pressurized with nitrogen through the short needle. About 5 mL of sample can typically be filtered with a single filter before clogging. In addition, for a subset of samples, the stopper was removed from the sample tube after filtering a small aliquot under nitrogen, and ~50 mL of groundwater was poured through a funnel coated with coarse cellulose fiber paper (Fisher Scientific Cat No. 09-790-12G) to remove particles >25 μm, without taking any special precautions to avoid contact with oxygen in the air.

Samples from the needle-sampler filtered under nitrogen were transferred into acid-cleaned scintillation vials and acidified to 1% HCl (Optima, Fisher Scientific). These aliquots were analyzed for As, Mn, and other groundwater constituents by high resolution inductively coupled plasma mass spectrometry (HR ICP-MS) (*14*). The detection limit of the method is ~0.1 μg/L for As, and the precision is on the order of 2%. Groundwater samples from three nests of monitoring wells located within a few meters of Sites A, B, and F in January 2001, June 2001, and January 2003, respectively, were also analyzed by HR ICP-MS.

The larger aliquots of groundwater (~50 mL) filtered through a funnel were immediately transferred to a reaction vessel for As analysis by arsine generation using the Hach EZ Arsenic kit (Product No. 2822800, The Hach Company, Loveland, Colorado). The Hach kit, and most field kits relying on arsine generation, requires visual comparison of the orange-brown color of an indicator strip with a reference scale. The scale provided with the Hach kit shows the color expected for As concentrations of 10, 30, 50, 100, 250, 500, and 900 μg/L. Results were recorded as the range of the closest reference points rather than by attempting to interpolate visually. The manufacturer's instructions were followed, with the exception that the duration of the reaction was doubled to 40 min before visually comparing the test strip with the provided color scale. A smaller aliquot of groundwater filtered through the funnel was taken up with a syringe and filtered a second time through a 0.4 μm syringe filter before acidification with Optima HCl. These aliquots were also analyzed by HR ICP-MS.

In addition to groundwater, the needle-sampler collects sediment from a known depth at a cost much lower than that of traditional coring methods. The quantity of silt and sand (~0.01−3 mm diameter) collected in the sample chamber generally varies between <1 g and ~50 g per deployment, depending on the size of the entry holes of the needle relative to the grain size distribution of the sampled horizon. The redox state of the sediment collected with the needle-sampler was determined by measuring with ferrozine the proportion of Fe(II) in the Fe fraction that is leached in hot 1.2 N HCl (*15*). At Sites A and F, profiles of Fe(II)/Fe for sediment collected with the needle sampler are compared with the same measurements performed on fresh cuttings recovered while installing wells in January 2002.

Results

Laboratory As Data. The groundwater As profiles generated with the needle-sampler at the three test sites reproduce the results obtained from the nearby monitoring wells (Figure 2). At Sites A and B, the profiles obtained with the needle-sampler and the monitoring wells show that As concentrations increase rapidly from <50 μg/L in the shallowest samples to 600 μg/L at ~12 m depth. Groundwater As levels then gradually decline to ~100 μg/L beyond this depth at Site B. At Site F, in contrast, dissolved As concentrations do not exceed 50 μg/L until ~15 m depth and reach a concentration of no more than 250 μg/L at 25 m depth. At Site A, samples collected with the needle-sampler and the monitoring wells indicate groundwater As concentrations below 10 μg/L at 30 m and several deeper intervals. Groundwater As concentrations for aliquots filtered first through the funnel and then a syringe filter are not significantly different from those obtained for samples filtered only once under nitrogen (Figure 2). Given the variable nature of the environment, the overall correspondence between the two data sets is encouraging because the monitoring wells integrate the composition of groundwater over a considerably wider depth range than the needle-sampler: the length of the screens at

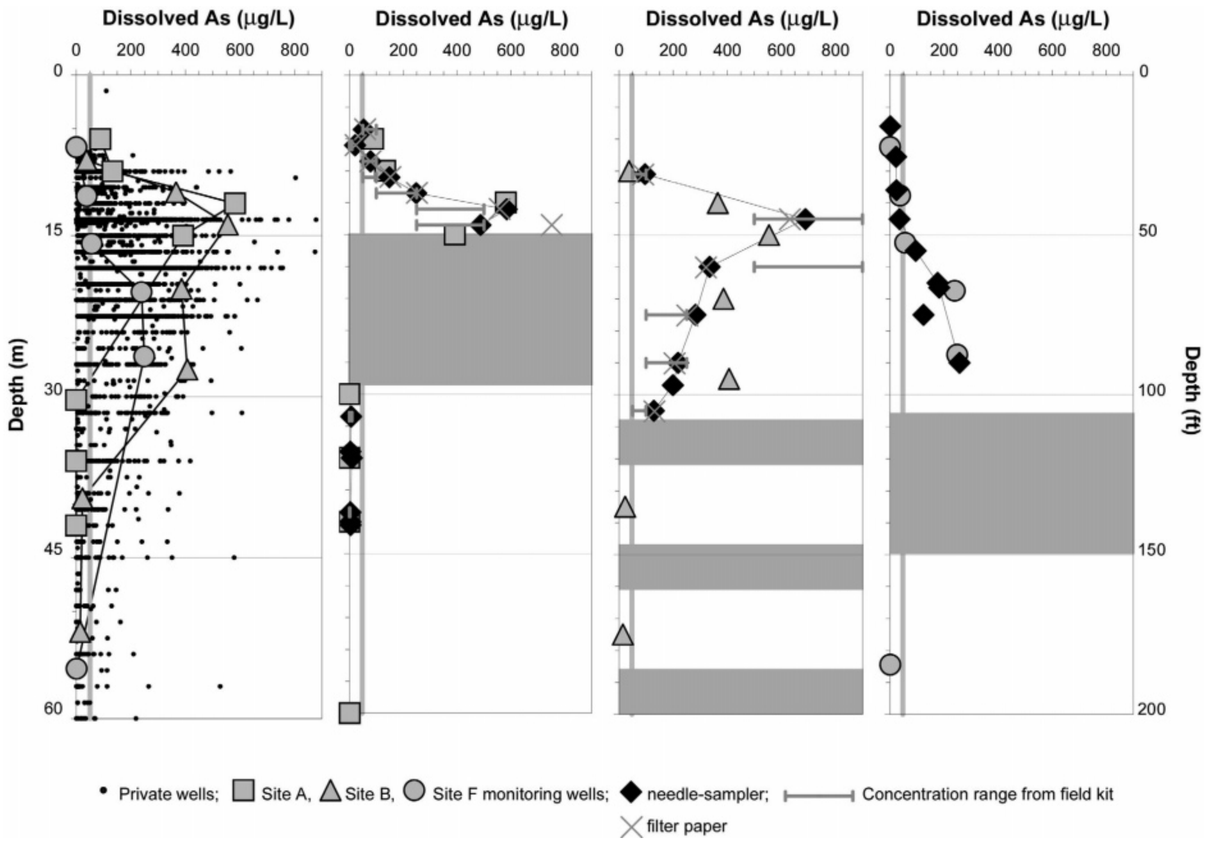


FIGURE 2. Panel to the left shows the distribution of As in groundwater as a function of depth throughout the 25 km^2 Araihazar study area determined from existing private wells (*10*) and at three selected sites based on nests of monitoring wells. Three panels to the right contain a detailed comparison of As concentrations in groundwater samples collected from monitoring wells and with the needle-sampler at Sites A, B, and F, respectively. The range of As concentrations determined with the Hach kit is indicated by horizontal error bars. The locations of clay layers from which groundwater cannot be extracted are shown in gray. A thick gray vertical line indicates the Bangladesh standard for As in drinking water of 50 μg/L.

the bottom of the monitoring wells is 90 cm, while the inlet holes of the needle-sampler span a distance of only 3 cm.

Field-Kit As data. The concentration ranges estimated from the Hach kit agree with the HR ICP-MS measurement for 13 out of a total of 15 samples analyzed both ways (Figure 2). The Hach kit correctly identified two deep intervals at Site A where groundwater meets the WHO guideline for As of 10 μg/L as well as several shallow intervals at Site F that meet the Bangladesh standard for drinking water of 50 μg/L (Figure 2). No interval containing over 50 μg/L As in groundwater was incorrectly identified by the Hach kit. In the case of the first discrepancy between laboratory and field measurements (Site A, 13 m), the actual concentration of 585 μg/L is only slightly greater than the Hach estimate of 250−500 μg/L. For the second discrepancy (Site B, 18 m), the actual concentration of 335 μg/L falls outside the 500−900 μg/L range estimated in the field. Overall, we see no compelling reason to abandon the use of the Hach kit based on these results as well as a broader comparison of laboratory results for ~800 wells in Araihazar with field testing independently conducted by BAMWSP (*18*), especially if laboratory measurements and the logistics involved in collecting a sample from a village and communicating the result back to the village are the only alternative (*19*).

Other Groundwater Constituents. Concentration profiles of the major cations Na, K, Mg, and Ca as well as the redox-sensitive constituents Fe, Mn, and S measured by HR ICP-MS for groundwater filtered through the funnel and then a syringe filter also generally match the composition of groundwater from the monitoring wells (See Figure 3 for Mn, respectively, and Supporting Information for other constituents). In combination with the As profiles, this confirms the integrity of the samples obtained with the needle-sampler despite the fact that the borehole contains water from a nearby well or a pond that is likely to be different in composition. The flow caused by maintaining the borehole filled with water (1−5 m of head) evidently does not affect the depth interval reached by the needle of the sampler during the 5−10 min interval required to deploy the needle-sampler after drilling is interrupted.

The data also show that Fe and Mn oxidation during filtration in ambient air is too slow to significantly reduce their respective concentrations (Supporting Information). This is significant because Mn is the constituent of Bangladesh groundwater of greatest health concern after As (*3*, *14*). Phosphate concentrations, on the other hand, are systematically lower in groundwater from the needle-sampler filtered twice than for the monitoring wells. The discrepancy probably reflects P adsorption on the small amount of Fe oxyhydroxides that precipitates on the paper filter (*20*).

For a half-dozen samples from Sites A and B, dissolved P and K concentrations in filtered water from the needle-sampler are much higher than in any of the monitoring wells (Supporting Information). These discrepancies are attributed to insufficient rinsing of the needle used for filtration after processing sediment slurries that were amended with 1 M $KHPO_4$ to measure the mobilizable As fraction on the sediment in October 2003 (*16*). Such extractions were not performed in October 2002 at Site F where K concentrations in groundwater from the needle-sampler match the steady increase in concentrations with depth indicated by the monitoring wells.

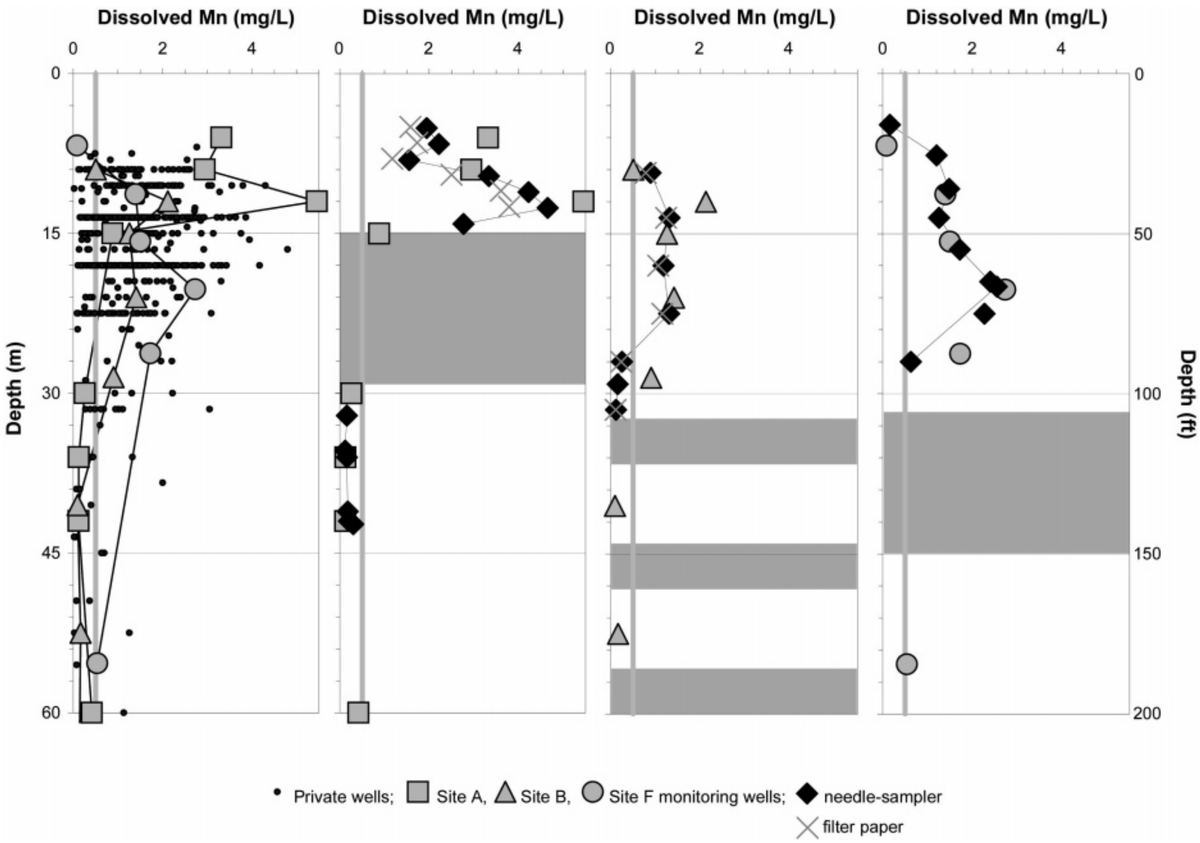


FIGURE 3. Panel to the left shows the distribution of Mn in groundwater as a function of depth throughout the 25 km² Araihazar study area determined from existing private wells (*14*) and at three selected sites based on nests of monitoring wells. Three panels to the right contain a detailed comparison of Mn concentrations in groundwater samples collected from monitoring wells and with the needle-sampler at Sites A, B, and F, respectively. A thick gray vertical line indicates the WHO guideline concentration for Mn of 0.5 mg/L in drinking water.

Sediment Data. The redox state of sediment collected with the needle-sampler follows the general depth trends indicated by the analysis of cuttings collected during previous drilling at Site A and Site F (Figure 4). The leachable Fe(II)/Fe fraction increases from ~0.2 to 0.6−0.7 in the shallow aquifers at both sites. At Site B, the Fe(II)/Fe ratio is relatively constant at ~0.7 over the depth intervals sampled by the needle-sampler. Both cuttings and sediment collected below the thick clay layer at Site A where As concentrations are <10 μg/L indicate a relatively low leachable Fe(II)/Fe ratio of 0.1−0.2.

Discussion

Profiling of Unconsolidated Aquifers. When considering the entire ~25 km² study area of Araihazar, the distribution of groundwater As and Mn as a function of depth clearly is highly variable in shallow aquifers (Figures 2 and 3). The data indicate a broad interval centered around 15 m where concentrations of both constituents are frequently elevated as well as a generally decreasing trend in concentrations at greater depths. These scatter is similar to that of As and Mn concentrations as a function depth observed throughout the country (*3*). At any single location in Bangladesh where nests of wells have been purposely installed, however, concentrations of As, Mn, and most other groundwater constituents have been shown to vary gradually as a function of depth (*3, 15, 16, 21*). The consistency of the data for groundwater samples collected with the needle-sampler with results from nearby monitoring wells indicates that groundwater properties also vary gradually on vertical scales < 1 m.

In addition to its use as a mapping tool, the needle-sampler provides an effective means of determining potential associations between dissolved As concentrations and sediment characteristics such as mineralogy, organic content, or the presence of certain microorganisms. This is an active topic of research because few systematic associations of this type have been convincingly demonstrated to date, in part because it is difficult to obtain groundwater and aquifer particles from exactly the same horizon using traditional methods (*3, 22, 23*). Although it has been shown that groundwater extracted from older aquifers characterized by the orange-brown color of predominantly Fe(III) oxyhydroxides typically contains little As, the processes leading to a very wide range of As concentrations in more reducing gray sediment remains unclear (*3, 15, 16, 24*).

From a research perspective, the needle-sampler is therefore a convenient tool for collecting transects of paired groundwater and sediment properties at the spatial scale that is appropriate for complex flood plain and deltaic environments. The needle-sampler can also be used to target locations of interest before the permanent installation of monitoring wells or the collection of sediment cores with a drill rig, both of which require considerably more planning and resources.

Targeting Aquifers for Drinking Water. Of greater significance in terms of human health is the demonstration that the needle-sampler, or possibly a slightly simplified version thereof, could be used in conjunction with a field kit to test groundwater from a particular depth before the installation of a well by a household or a village community. In Araihazar, for instance, geological transitions below which groundwater As concentrations are systematically low can often be identified within a single village on the basis of the depth distribution of As in existing wells (*25*). The depth to such aquifers varies considerably from one neighboring village to another as well as regionally, however (*3, 10, 16,*

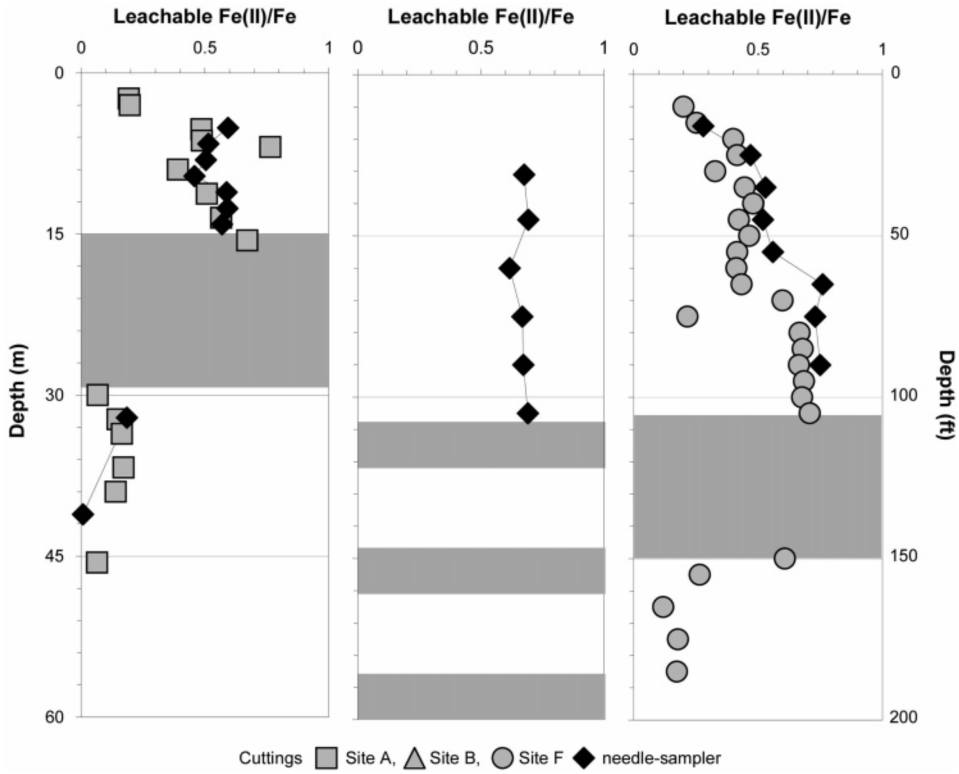


FIGURE 4. Comparison of the depth distribution of the leachable Fe(II)/Fe fraction of the sediment at Sites A, B, and F for samples collected with the needle sampler and cuttings recovered during drilling.

25). When this information is available, the needle-sampler could be used just once as a final check before the actual installation of well. Collecting a sample of groundwater with the needle-sampler and testing it with the Hach kit would delay the installation of a well by no more than 1 h. When little is known about the local depth distribution, identifying the transition to groundwater that is sufficiently low in As may require several deployments of the needle-sampler. Such testing could be conducted by the same teams of local drillers that installed ~95% of the existing wells in the country.

The proportion of existing wells in Bangladesh that exceed the WHO guideline for Mn is very high (*3*, *14*). As a precautionary measure, groundwater should therefore also be tested for Mn before proceeding with the installation of a well. The health effects of Mn levels in drinking water that exceed the WHO guideline of 0.5 mg/L are poorly known but could be significant (*9*). Fortunately, there are a number of reliable kits for measuring Mn at concentrations above 0.1 mg/L.

It is unrealistic to expect the hundreds of teams of drillers operating in Bangladesh to include a field kit for As and Mn as well as the needle-sampler with their standard equipment soon. What is conceivable at an early stage is the systematic use and refinement of the device by engineers working for the Bangladesh government as well as nongovernmental organizations involved in As mitigation. With the exception of perhaps the needle itself and the hand-vacuum pump (which could be eliminated by doubling the size of the sample chamber and relying on hydrostatic pressure to yield ~50 mL of groundwater), all components of the needle-sampler could be produced in Bangladesh. Over time, households and drillers will hopefully recognize the value of the device for increasing the likelihood of installing a well that meets drinking water standards for both As and Mn.

Acknowledgments

We thank Mohammed Feroz Miah, his brother Abu Taleb, and their respective teams of drillers for developing the approach with us over several field trips. Their energy and willingness to experiment have been an inspiration throughout this project. Conversations with Z. Aziz, R. Dhar, J. M. Garnier, B. Mailloux, J. Rose, P. Schlosser, W. Smethie, M. Stute, and Y. Zheng also stimulated the development of the needle-sampler. This study was supported by NIEHS Superfund Basic Research Program grant NIH 1 P42 ES10349. This is Lamont Doherty Earth Observatory contribution number 6677.

Supporting Information Available

Table of concentrations and technical drawings of all the components of the needle-sampler. This material is available free of charge via the Internet at http://pubs.acs.org.

Literature Cited

(1) Dhar, R. K.; Biswas, B. K.; Samanta, G.; Mandal, B. K.; Chakraborti, D.; Roy, S.; Jafar, A.; Islam, A.; Ara, G.; Kabir, S.; Khan, A. W.; Ahmed, S. A.; Hadi, S. A. Groundwater arsenic calamity in Bangladesh. *Curr. Sci.* **1997**, *73*, 48−59.

(2) Mandal, B. K.; Chowdhury, T. R.; Samanta, G.; Mukherjee, D. P.; Chanda, C. R.; Saha, K. C.; Chakraborti, D. Impact of safe water for drinking and cooking on five arsenic-affected families for 2 years in West Bengal, India. *Sci. Total Environ.* **1998**, *218*, 185−201.

(3) BGS and DPHE. *Arsenic contamination of groundwater in Bangladesh*; Kinniburgh, D. G., Smedley, P. L., Eds.; Final Report, BGS Technical Report WC/00/19, British Geological Survey, Keyworth, U.K, 2001.

(4) Berg, M.; Tran, H. C.; Nguyen, T. C.; Pham, H. V.; Schertenleib, R.; Giger, W. Arsenic contamination of groundwater and drinking water in Vietnam: A human health threat. *Environ. Sci. Technol.* **2001**, *35*, 2621−2626.

(5) Smith, A. H.; Lingas, E. O.; Rahman, M. Contamination of drinking-water by arsenic in Bangladesh: a public health emergency. *Bull. World Health Organization* **2000**, *78*, 1093−1103.

(6) Ahsan, H.; Perrin, M.; Rahman, A.; Hasnat, A.; Parvez, M. F.; Brandt-Rauf, P.; Zheng, Y.; Stute, M.; van Geen, A.; Graziano, J. Association between drinking water and urinary arsenic levels

and skin lesions in Bangladesh. *J. Occup. Environ. Med.* **2000**, *42* (12), 1195−1201.
(7) Yu, W. H.; Harvey, C. M.; Harvey, C. F. Arsenic in groundwater in Bangladesh: A geostatistical and epidemiological framework for evaluating health effects and potential remedies. *Water Resour. Res.* **2003**, *39* (6), 1146, doi: 10.1029/2002WR001327.
(8) Chen, Y.; Ahsan, H. Cancer burden from arsenic in drinking water in Bangladesh. *Am. J. Public Health* **2004**, *94* (5), 741−744.
(9) Wasserman, G. A.; Liu, X.; Parvez, F.; Ahsan, H.; Factor-Litvak, P.; van Geen, A.; Cheng, Z.; Slavkovich, V.; Hussain, I.; Momotaj, H.; Graziano, J. H. Water arsenic exposure and children's intellectual function in Araihazar, Bangladesh. *Environ. Health Perspect.* **2004**, *112*, 1329−1333.
(10) van Geen, A.; Zheng, Y.; Versteeg, R.; Stute, M.; Horneman, A.; Dhar, R.; Steckler, M.; Gelman, A.; Small, C.; Ahsan, H.; Graziano, J.; Hussein, I.; Ahmed, K. M. Spatial variability of arsenic in 6000 tube wells in a 25 km2 area of Bangladesh. *Water Resour. Res.* **2003**, *39* (5), 1140, doi: 10.1029/2002WR001617.
(11) BRAC. *Combating a deadly menace: Early experiences with a community-based arsenic mitigation project in Bangladesh*; Research Monograph Series No. 16, Dhaka, Bangladesh, 2000.
(12) van Geen, A.; Ahsan, H.; Horneman, A. H.; Dhar, R. K.; Zheng, Y.; Hussain, I.; Ahmed, K. M.; Gelman, A.; Stute, M.; Simpson, H. J.; Wallace, S.; Small, C.; Parvez, F.; Slavkovich, V.; LoIacono, N. J.; Becker, M.; Cheng, Z.; Momotaj, H.; Shahnewaz, M.; Seddique, A. A.; Graziano, J. H. Promotion of well-switching to mitigate the current arsenic crisis in Bangladesh. *Bull. World Health Organization* **2002**, *80*, 732−737.
(13) van Geen, A.; Ahmed, K. M.; Seddique, A. A.; Shamsudduha, M. Community wells to mitigate the current arsenic crisis in Bangladesh. *Bull. World Health Organization* **2003**, *82*, 632−638.
(14) Cheng, Z.; Zheng, Y.; Mortlock, R.; van Geen, A. Rapid multi-element analysis of groundwater by high-resolution inductively coupled plasma mass spectrometry. *Anal. Bioanal. Chem.* **2004**, *379*, 513−518.
(15) Horneman, A.; van Geen, A.; Kent, D. V.; Mathe, P. E.; Zheng, Y.; Dhar, R. K.; O'Connell, S.; Hoque, M. A.; Aziz, Z.; Shamsudduha, M.; Seddique, A. A.; Ahmed, M. A. Decoupling of As and Fe release to Bangladesh groundwater under reducing conditions. Part I: Evidence from sediment profiles. *Geochim. Cosmochim. Acta* **2004**, *68*, 3459−3473.
(16) Zheng, Y.; van Geen, A.; Stute, M.; Dhar, R.; Mo, Z.; Cheng, Z.; Horneman, A.; Gavrieli, I.; Simpson, H. J.; Versteeg, R.; Steckler, M.; Grazioli-Venier, A.; Goodbred, S.; Shanewaz, M.; Shamsudduha, M.; Ahmed, K. M. Geochemical and hydrogeological contrasts between shallow and deep aquifers in two villages of Araihazar, Bangladesh: Implications for arsenic mobility. Submitted to *Geochim. Cosmochim. Acta*, July 2004.
(17) Ali, M. Review of drilling and tubewell technology for groundwater irrigation. In *Groundwater Resources and Development in Bangladesh − Background to the Arsenic Crisis, Agricultural Potential and the Environment*; Rahman, A. A., Ravenscroft, P., Eds.; University Press Ltd.: Dhaka, 2003.
(18) van Geen, A.; Cheng, Z.; Seddique, A. A.; Hoque, M. A.; Gelman, A.; Graziano, J. H.; Ahsan, H.; Parvez, F.; Ahmed, K. M. Reliability of a commercial kit to test groundwater for arsenic in Bangladesh. *Environ. Sci. Technol.*, **2004**, in press.
(19) Rhaman, M. M.; Mukherjee, D.; Sengupta, M. K.; Chowdhury, U. K.; Lodh, D.; Chanda, C. R.; Roy, S.; Selim, Md.; Quamruzzam, Q.; Milton, A. H.; Shadidullah, S. M.; Rahman, Md. T.; Chakraborti, D. Effectiveness and reliability of arsenic field testing kits: Are the million dollar screening projects effective or not? *Environ. Sci. Technol.* **2002**, *36*, 5385−5394.
(20) Zheng, Y.; Stute, M.; van Geen, A.; Gavrieli, I.; Dhar, R.; Simpson, H. J.; Schlosser, P.; Ahmed, K. M. Redox control of arsenic mobilization in Bangladesh groundwater. *Appl. Geochem.* **2004**, *19*, 201−214.
(21) Harvey, C. F.; Swartz, C. H.; Baruzzaman, A. B. M.; Keon-Blute, N.; Yu, W.; Ali, M. A.; Jay, J.; Beckie, R.; Niedan, V.; Brabander, D.; Oates, P. M.; Ashfaque, K. N.; Islam, S.; Hemond, H. F.; Ahmed, M. F. Arsenic mobility and groundwater extraction in Bangladesh. *Science* **2002**, *298*, 1602−1606.
(22) McArthur, J. M.; Banerjee, D. M.; Hudson-Edwards, K. A.; Mishra, R.; Purohit, R.; Ravenscroft, P.; Cronin, A.; Howarth, R. J.; Chatterjee, A.; Talukder, T.; Lowry, D.; Houghton, S.; Chadha, D. K. Natural organic matter in sedimentary basins and its relation to arsenic in anoxic groundwater: the example of West Bengal and its worldwide implications. *Appl. Geochem.* **2004**, *19* (8), 1255−1293.
(23) Islam, F. S.; Gault, A. G.; Boothman, C.; Polya, D. A.; Charnock, J. M.; Chatterjee, D.; Lloyd, J. Role of metal-reducing bacteria in arsenic release from Bengal delta sediments. *Nature* **2004**, *430*, 68−71.
(24) van Geen, A.; Thoral, S.; Rose, J.; Garnier, J. M.; Zheng, Y.; Bottero, J. Y. Decoupling of As and Fe release to Bangladesh groundwater under reducing conditions. Part II: Evidence from sediment incubations. *Geochim. Cosmochim. Acta* **2004**, *68*, 3475−3486.
(25) Gelman, A.; Trevisani, M.; Lu, H.; van Geen, A. Direct data manipulation for local decision analysis, as applied to the problem of arsenic in drinking water from tube wells in Bangladesh. *Risk Analysis* **2004**, in press.

Received for review May 3, 2004. Revised manuscript received September 2, 2004. Accepted September 6, 2004.

ES049323B

	Depth (ft)	As (ug/L)	Mn (mg/L)	Na (mg/L)	Mg (mg/L)	P (mg/L)	S (mg/L)	K (mg/L)	Ca (mg/L)	Fe (mg/L)
Monitoring wells	20	89	3.3	37.3	22.8	0.8	11.3	59.8	51.2	17.8
Site A Jan '01	30	133	2.9	18.6	23.8	0.5	6.2	4.6	42.4	4.6
	40	582	5.5	26.8	25.3	1.0	2.7	4.8	59.4	7.3
	50	392	0.9	38.2	32.6	0.7	0.2	5.1	56.6	11.9
	101	0	0.3	75.7	7.0	0.1	1.0	1.1	11.1	0.0
	120	0	0.1	57.7	5.8	0.2	1.3	1.1	16.7	0.1
	140	0	0.1	51.2	5.4	0.2	1.3	1.1	17.1	0.1
	274	1	0.4	46.7	12.1	0.3	1.3	1.8	24.7	0.3
Needle-sampler	17	53	1.9	26.2	15.4		22.3		46.0	29.3
Site A Oct '02	22	21	2.2	32.2	18.3		10.8		41.9	1.8
	27	78	1.6	40.4	15.5		4.3		32.9	2.5
	32	148	3.3	18.4	15.3		3.3		41.1	7.2
	37	249	4.2	20.0	17.0		0.3		49.6	9.3
	42	585	4.7	25.6	24.2		0.3		73.7	14.6
	47	488	2.8	25.2	22.0		0.3		67.8	12.9
	107	7	0.2	53.7	6.8		1.7		10.7	0.0
	118	4	0.1	42.7	5.9		1.5		15.8	0.1
	120	9	0.2	43.8	5.8		1.4		11.6	0.0
	137	4	0.2	41.1	5.7		1.5		16.5	0.0
	141	5	0.3	45.2	6.7		4.1		15.4	0.0
	140	4	0.2	68.6	5.6		3.9		14.6	0.0
Needle-sampler	17	54	1.7	34.8	14.7	0.3	24.8	43.2	44.4	46.9
Site A Oct '02	22	19	1.8	33.7	16.1	0.3	12.2	29.8	37.9	2.2
Filter paper	27	74	1.3	21.1	13.9	5.2	4.7	10.2	30.3	2.9
	32	148	2.6	24.1	13.5	0.2	3.7	5.1	34.4	9.5
	37	247	3.7	23.9	14.8	0.3	0.8	5.4	46.3	14.0
	42	554	3.9	30.2	20.2	0.2	0.8	6.7	65.2	20.7
	47	747	7.4	37.8	22.0	0.7	0.9	7.5	60.3	8.0
Monitoring wells	27	37	0.5	100.5	50.2	2.8	14.9	6.0	117.4	13.1
Site B Jun '01	37	366	2.1			1.3	7.6			8.3
	47	555	1.3	46.8	40.5	1.4	6.7	5.9	119.9	14.2
	67	386	1.4	40.5	34.7	1.5	0.1	4.7	103.4	11.5
	92	407	0.9			1.6	0.1			17.7
	132	22	0.1	23.2	38.0	1.3	0.0	5.7	41.5	6.2
	173	14	0.2	53.8	17.2	0.5	0.0	2.2	29.1	3.4
	291	11	0.1	59.3	7.4	0.1	0.0	1.6	15.5	0.6
Needle-sampler	31	96	0.9	83.5	31.7		13.1		112.8	14.6
Site B Oct'02	45	689	1.3	54.2	30.0		9.8		141.6	11.0
	60	335	1.2	25.1	25.8		0.3		101.9	8.8
	75	283	1.3	21.5	24.9		0.3		101.0	13.8
	90	218	0.3	37.0	23.0		0.3		92.3	8.8
	97	199	0.2	40.0	26.9		0.3		81.9	4.9
	105	129	0.1	53.3	30.2		0.4		59.0	5.3
Needle-sampler	31	80	0.8	97.3	33.1	0.0	13.5	6.9	108.3	12.8
Site B Oct'02	45	623	1.2	64.7	28.4	0.3	10.6	7.3	131.7	14.1
Filter paper	60	312	1.1	30.7	22.1	0.0	0.8	5.5	93.3	10.4
	75	243	1.1	28.9	22.5	0.0	1.0	5.6	96.6	14.9
	90	196	0.2	45.9	19.8	0.2	0.9	7.2	83.2	8.5
	105	122	0.1	60.9	27.4	0.6	0.9	8.6	52.0	2.1
Monitoring wells	23	1	0.1	13.5	14.6	0.0		3.2	28.8	0.3
Site F Jan'03	38	38	1.4	1.3	7.7	0.1		2.6	15.4	3.1
	53	57	1.5	1.7	11.3	0.1		2.6	28.5	1.2
	68	240	2.7	6.3	16.2	0.5		3.5	50.7	1.5
	88	249	1.7	8.3	17.7	1.0		4.5	76.3	25.6
	185	2	0.5	226.8	6.7	0.2		1.5	13.5	0.9
Needle-sampler	16	1	0.2	12.1	7.7	0.2	1.3	2.7	14.7	0.0
Site F Oct'02	26	23	1.2	13.7	13.2	0.1	1.3	3.3	25.9	0.7
	36	25	1.5	16.4	9.3	0.1	0.4	3.4	18.8	0.3
	45	35	1.3	15.4	10.5	0.5	1.3	3.0	23.4	0.0
	55	96	1.7	24.4	12.0	0.5	0.4	3.8	38.5	0.0
	65	177	2.4	71.9	20.0	0.3	0.7	5.6	52.6	0.5
	67	183	2.5	26.5	19.0	0.3	0.8	4.8	52.6	0.3
	75	124	2.3	29.4	17.8	0.0	0.1	4.5	67.9	0.4
	90	257	0.6	36.4	19.4	0.2	0.5	6.6	82.0	2.6

SAMPLE TUBE

3/4" CLEAR PVC PIPE SCH 40
LENGTH 12"
3/4" NPT FEMALE x 3/4" SOCKET ADAPTER
1" X 1/8 CLEAR PVC DISC.

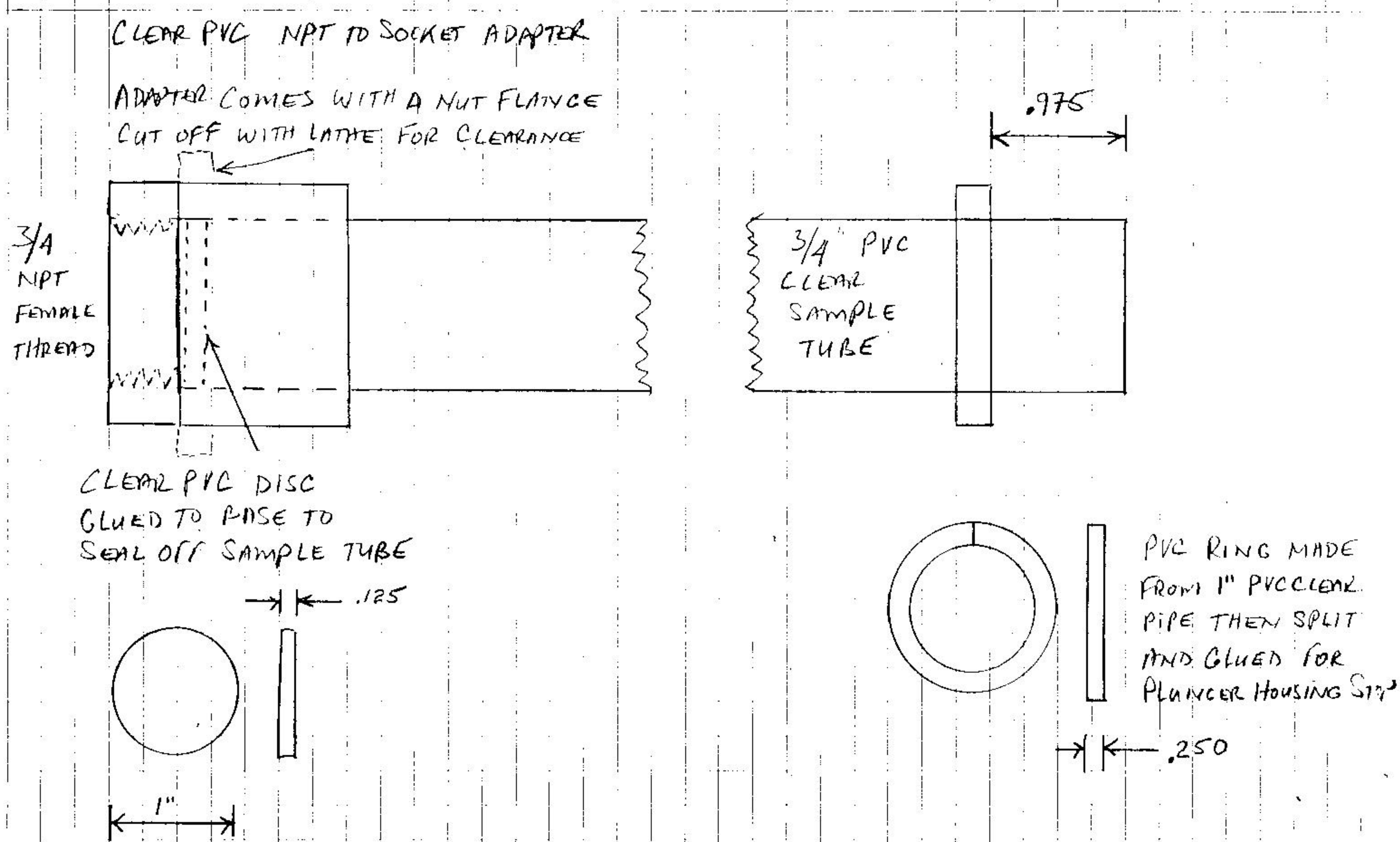
SAMPLE NEEDLES - SEE DRAWING

PLUNGER

1" DIA PVC STOCK OD 1.030
LENGTH 2"
SLOT WIDTH .250
SLOT DEPTH .075
SLOT LENGTH 1.600
SET SCREWS FOR NEEDLE LOCKS 1/4-20X3/8 CUP POINT STAINLESS STEEL
HOLE SIZE IN PLUNGER FOR NEEDLES 3.5 MM

PLUNGER HOUSING

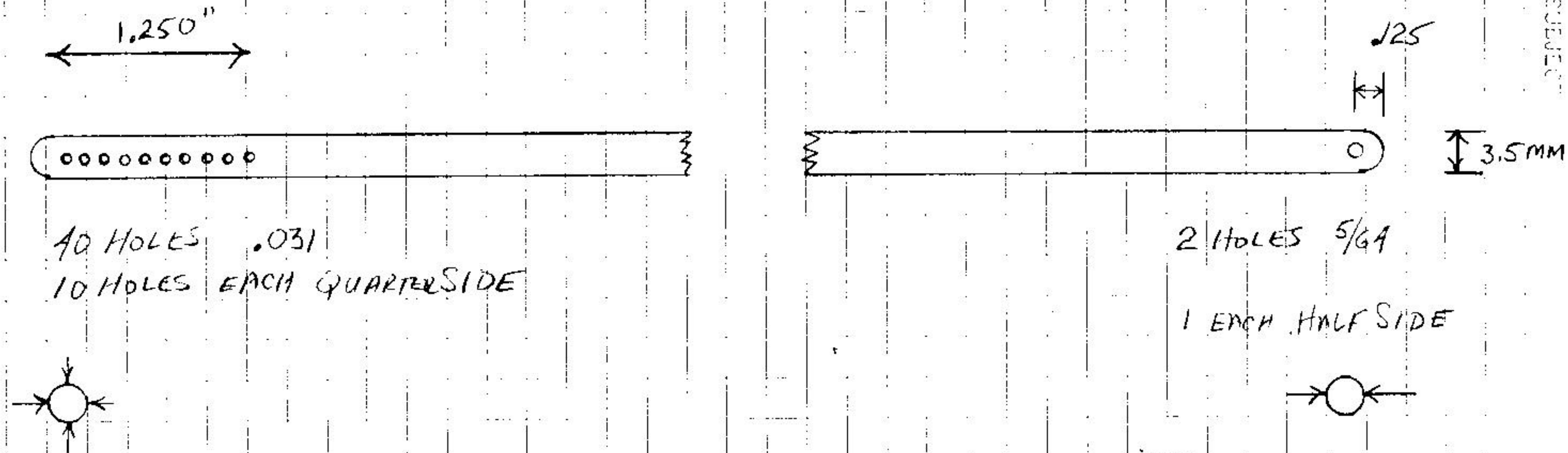
1" PVC CLEAR PIPE SCH 40 BORED OUT TO 1.050" ID
LENGTH 3.1"
2 TAPPED 1/4-20 HOLES FOR PLUNGER ADJUST USING 1/4-20X3/16 CUP POINT STAINLESS STEEL SET SCREWS
4 1/4" HOLES FOR WATER VENTING
2-4 1/4-20 TAPPED HOLES FOR LOCKING PLUNGER TO SAMPLE TUBE USING 1/4-20X3/16 CUP POINT SET SCREWS STAINLESS STEEL



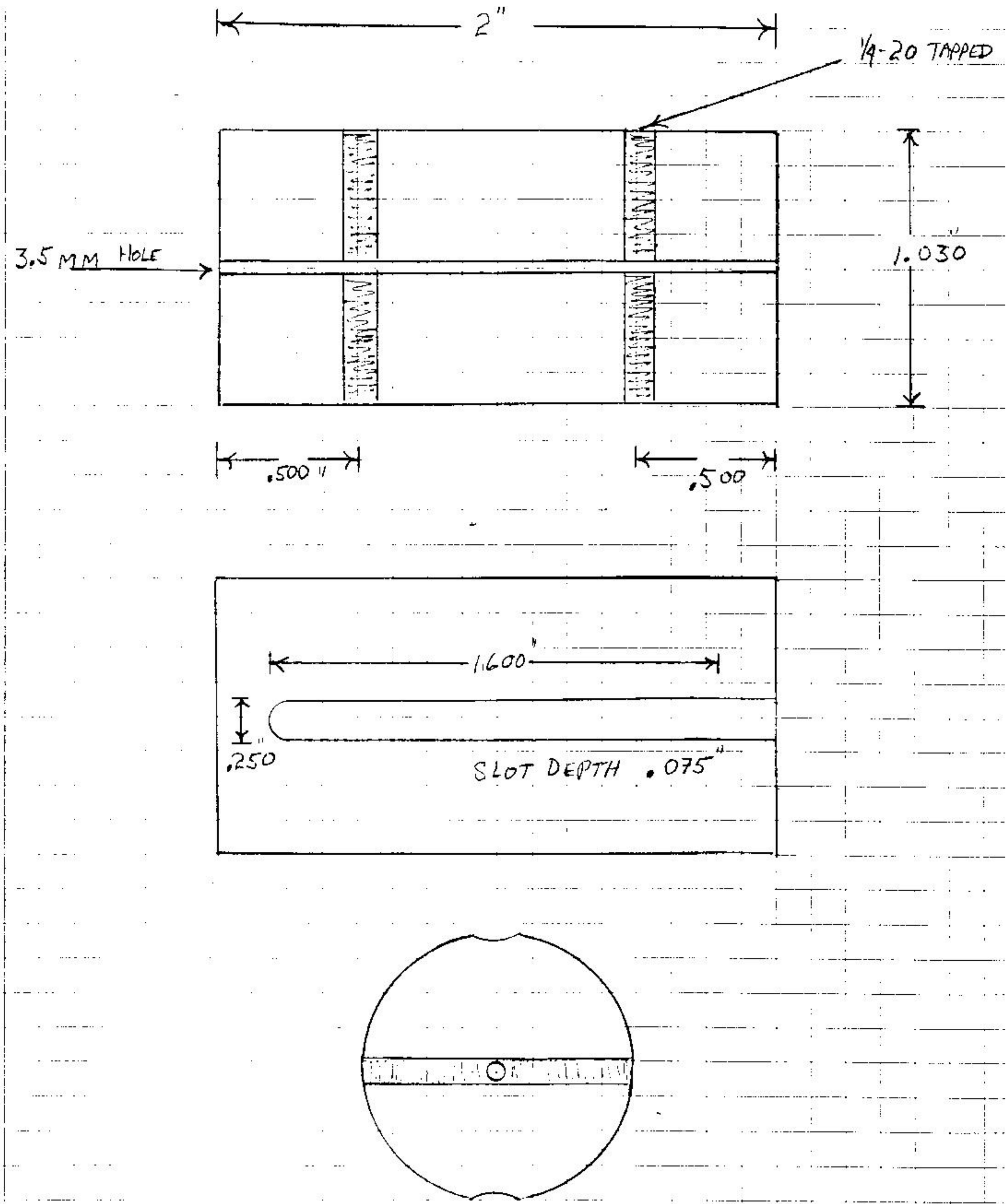
CLEAR PVC NPT TO SOCKET ADAPTER
ADAPTER COMES WITH A NUT FLANGE CUT OFF WITH LATHE FOR CLEARANCE
.975
3/4 NPT FEMALE THREAD
3/4" PVC CLEAR SAMPLE TUBE
CLEAR PVC DISC GLUED TO BASE TO SEAL OFF SAMPLE TUBE
.125
1"
PVC RING MADE FROM 1" PVC CLEAR PIPE THEN SPLIT AND GLUED FOR PLUNGER HOUSING STOP
.250

DATE SUBJECT PROJECT NO.

NEEDLE HOLE LAYOUT

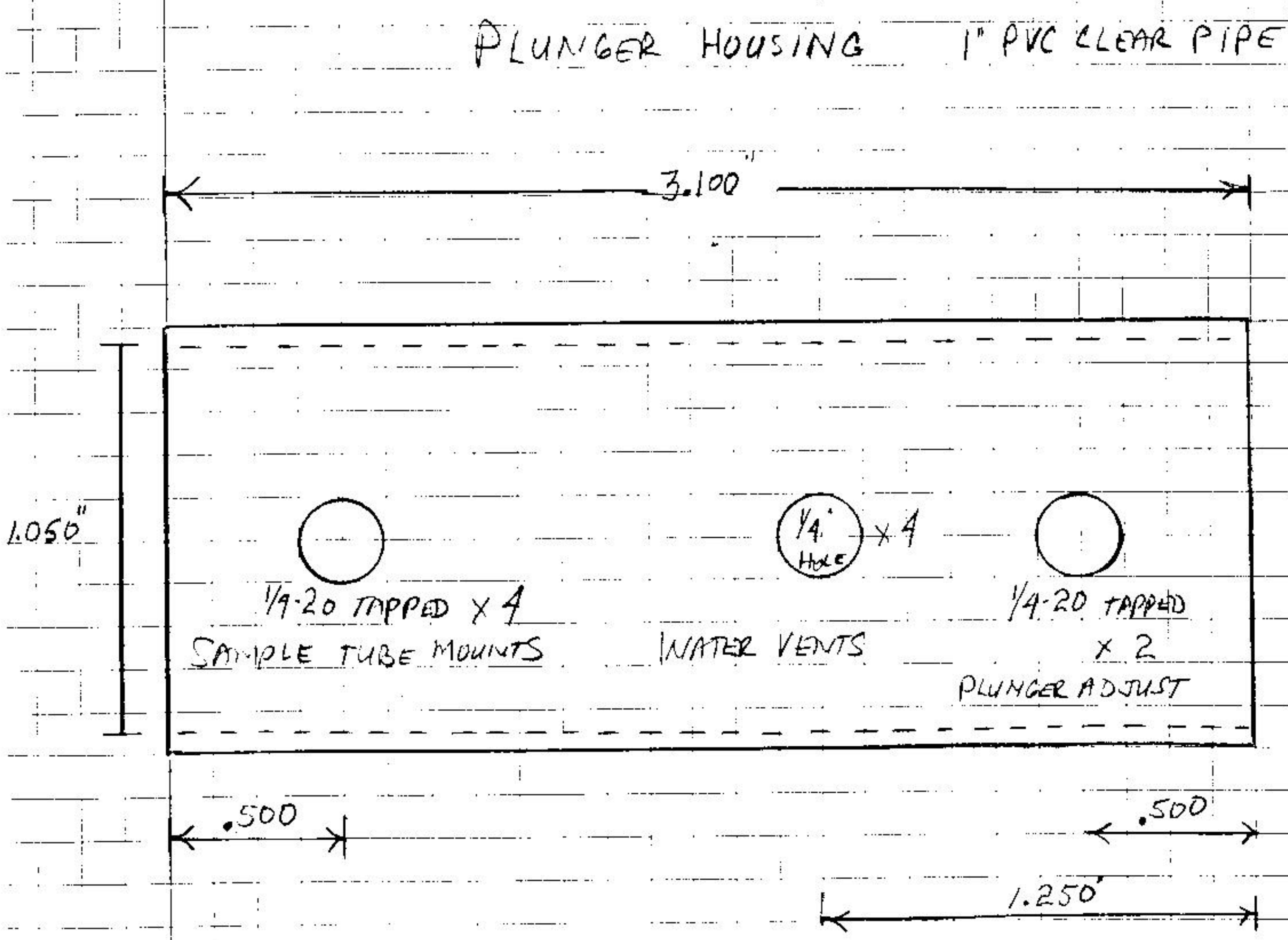


PLUNGER 1" DIA PVC STOCK OD 1.030"



TNESSED AND UNDERST

IGNED DATE SIGNED



WITNESSED AND UNDERSTOOD