Risk Assessment of Ingestion of Arsenic-Contaminated Water among Adults in Bandlaguda, India

Aneena S. Pokkamthanam[1], Anne M. Riederer[1], Raghupathy Anchala[2]

1 Department of Environmental Health, Rollins School of Public Health, Emory University, Atlanta, USA
2 Public Health Foundation, Indian Institute of Public Health, Hyderabad, India

Corresponding Author:
Aneena Pokkamthanam
769 Yorkshire Way
Corona, CA 92879
USA
Tel.: (909) 374-7836
a.s.pokkam@gmail.com

Background. The Indian Government describes the Patancheru Industrial Development Area (IDA) near Hyderabad as a heavily polluted site. Previous studies show levels of arsenic in ground and surface water that exceed the national drinking water standard.
Objectives. We conducted a pilot study to characterize potential non-cancer and cancer risks associated with ingesting arsenic-contaminated water by adult residents of Bandlaguda, a village in the Patancheru IDA.
Methods. We used United States Environmental Protection Agency (USEPA) equations to calculate hazard quotients (for non-cancer outcomes) and excess cancer risks. Inputs included information on water sources and consumption that we collected from a representative sample of residents using a standardized questionnaire, and arsenic concentration data from a previous study. We calculated point estimates of risk and used @RISK software to conduct probabilistic simulations and perform sensitivity analyses.
Results. In both the point and probabilistic analyses, the mean hazard quotients exceeded 1 for both men and women, indicating potentially elevated risk of non-cancer outcomes. Mean lifetime excess cancer risks using the USEPA default 70-year life expectancy were 0.01 (i.e., 1 in 100) for men and 0.006 (i.e., 6 in 1,000) for women. Mean excess risks using Indian life expectancies were 0.01 for men and 0.007 for women. Sensitivity analyses identified the reference dose and cancer slope factor as the most influential input variables.
Conclusions. Our results show that arsenic in water consumed by Bandlaguda adults may be associated with both non-cancer and cancer risks. There is an urgent need to identify unsafe sources of drinking water in this community and educate residents on the hazards of using them.
Keywords. risk assessment, arsenic, water, India, Bandlaguda, Patancheru.
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Introduction

Established in the mid-1970s, the Patancheru IDA is approximately 120 km^2,[1] and located 25 km from Hyderabad.[2] One of 13 IDAs around Hyderabad, it has been identified as one of the most polluted areas in India by the Central Pollution Control Board (CPCB).[2,3] All of Hyderabad's IDAs are located in the sub-basin of the Nakkavagu River, a tributary of the Manjira River, a main source of drinking water for the region.[3]

Previous studies[4,2] report arsenic levels in ground and surface water in and around the Patancheru IDA that exceed the World Health Organization (WHO) and the Indian Government standard of 0.01 mg/L.[5,6] In the most recent study, arsenic concentrations in surface water ranged from 0.006 - 0.1 mg/L, with a mean of 0.3 (±0.03) mg/L, while groundwater concentrations ranged from 0.003-1.3 mg/L, with a mean of 0.1 (±0.3) mg/L.[2] Researchers speculate that the pharmaceutical, tanning, fertilizer and pesticide industries are anthropogenic sources of arsenic pollution in the area.[4,2] Natural sources such as leaching from aquifer materials can also contaminate groundwater with arsenic. Although it is generally difficult to differentiate arsenic from natural/geologic versus anthropogenic sources, researchers cite the high variability of arsenic concentrations in local surface waters as evidence of industrial contamination.[2] Regardless of source, ingestion of contaminated ground and/or surface water is an important potential route of arsenic exposure for local residents.[7]

We conducted a pilot study to characterize potential non-cancer and cancer risks associated with ingestion of arsenic-contaminated water among adult (i.e., 18+ years old) residents of Bandlaguda, a village in the Patencheru IDA. The study was a collaboration among researchers from Emory University (Atlanta, USA), the Indian Institute of Public Health (Hyderabad, India) and the Public Health Foundation of India (Hyderabad, India), and was approved by Emory's Institutional Review Board. We chose Bandlaguda because it had the highest concentrations of groundwater arsenic in a previous study.[2]

Our objectives were to: 1) calculate the average daily dose (ADD) and lifetime average daily dose (LADD) of arsenic from ingestion of water among Bandlaguda men and women, 2) calculate point estimates of the risk of non-cancer (hyperpigmentation, keratosis, and vascular disesases) and cancer (skin cancer) outcomes associated with this intake, and 3) calculate potential distributions of non-cancer and cancer risks using a probabilistic modeling approach. We collected information on water sources and consumption from residents using a standardized questionnaire in July 2009. We used this information to estimate water consumption rates and combined these with arsenic data to estimate ADD and LADD for our study participants.[2] We only considered ingestion (versus dermal or inhalation) exposure because this is thought to be the most important exposure pathway for people who are not occupationally exposed.[8,9]

Abbreviations and Definitions:

ADD	average daily dose	*IIPS*	International Institute for Population ciences
AT	averaging time	*IR*	intake rate
BIS	Bureau of Indian Standards	*LADD*	lifetime average daily dose
CSF	cancer slope factor	*RfD*	reference dose
CPCB	Central Pollution Control Board	*UI*	uncertainty interval
CDF	cumulative density function	*USEPA*	United States Environmental Protection Agency
IDA	Industrial Development Area	*WHO*	World Health Organization

Methods

Study Site

Bandlaguda is comprised of four colonies (Bandlaguda, Marx Nagar, Netaji Nagar, Balaji Nagar) covering 139 hectares, with 74 hectares consisting of industrial area.[10] The most recent (2001) census population was 5,023.[11] Of 1,108 houses in the village, 1,015 were below the Indian poverty line.[10]

The main sources of water in Bandlaguda are bore wells, the Manjira River, and deep wells. The panchayat (e.g., local government), Manjira Water Board, and the Pennar Industry supply water to residents. The Manjira Water Board is a private water treatment plant, while Pennar Industry is a local resin-producing company. Manjira water is treated river water, provided either by the Manjira Water Board,or collected via unofficial connection along National Highway 9 (NH-9) or a leak in a water pipe connected to the Pennar compound. The panchayat reportedly distributes Manjira water 1-2 times per week to each colony. Anecdotal reports note that the panchayat mixes bore water with Manjira water if the quantity of Manjira water on a given day cannot meet village needs (personal communication between A. Pokkamthanam and village elder, 2009). The proportion of mixing is unknown and likely changes based on need.

Exposure Survey

We used proportional random sampling to select representative households in Bandlaguda to include in our exposure survey. We interviewed one eligible adult from each house. Eligibility was determined by the ability to respond to questions asked, as well as age and sex. The sex of the person interviewed alternated: if a man was interviewed first, then a woman was interviewed next, and so on (further details presented in the Supplemental Material). We developed a questionnaire to collect data on demographics, body weight/height, and water sources, usage, and treatment methods, using questions adapted from India's National Family and Health Survey[12] and the Clark Environmental Health Survey.[13] The questionnaire was translated from English to Telugu, then back-translated by a third party to check translation quality.

Two research assistants from a local university interviewed 100 households over a two-week period. They were fluent in Telugu and Hindi, and trained on questionnaire administration, informed consent procedures, techniques for reducing interviewer bias, and cultural appropriateness. Interviews were audio-recorded for quality control if participants verbally consented.

Data Analysis

We double-entered the questionnaire data into Microsoft Excel (Microsoft Corporation, Redmond, Washington), cross-checked them to identify discrepancies, and imported the database into SAS 9.2 (SAS Institute, Inc., Cary, NC) for statistical analysis. Details on our exploratory data analyses as well as the multivariable regression analyses we conducted to identify factors associated with exposure to arsenic-contaminated water are included in the Supplemental Material.

Arsenic Intake Rates

We calculated arsenic intake rates using general formulas adapted from USEPA policy[14]:

Total daily arsenic intake from water (IR) (mg/day) = $IR_{direct} + IR_{indirect}$ (1)

where:

IR_{direct} (mg/day) = [$\text{consumption}_{\text{drinking water}}$ (L/day) + $\text{consumption}_{\text{water from mixed drinks}}$ (L/day)] × $\text{arsenic}_{\text{water}}$ (mg/L) (2)

$IR_{indirect}$ (mg/day) = $\text{consumption}_{\text{water from food}}$ (L/day) × $\text{arsenic}_{\text{water}}$ (mg/L) (3)

For drinking water consumption, we used the L/day of drinking water reported by each participant. For water from mixed drinks, we used the reported L/day used to prepare drinks like tea. For water from food, we considered only water used to cook rice and dal, the most frequently eaten foods —97% and 53% of participants, respectively, reported having consumed rice and/or dal during the 24 hours before the interview. Because participants could not precisely estimate the amount of water used to cook these foods, we used proxy values from the U.S. Department of Agriculture's Food and Nutrient Database for Dietary Studies recipe database.[15,16] Specifically, we considered one cup of cooked rice to have 0.1 L of water and one cup of cooked dal to have 0.2 L of water (details provided in the Supplemental Material).

For the arsenic concentration in water, we used groundwater data along with our own assumptions about how much groundwater (i.e., bore, deep well) was mixed with Manjira River water for Bandlaguda residents.[2] For the bore water concentration,we generated a map of Banglaguda using Google Earth™ (2005) and georeferenced it to a previously used sampling map (details in the Supplemental Material).[2] We then identified six previously used sampling sites within 1 km of the Bandlaguda village boundaries and selected data from these sites as our bore/well water concentration estimates.[2] Arsenic concentrations from these sites ranged from 0.009-1.26 mg/L. We used the mean value —0.5 mg/L—in our point estimates of health risk, and the full distribution of values in our probabilistic models.

To estimate arsenic concentrations of Manjira water, water from Pennar Industry and the Manjira Water Board, and bottled water, we used the lowest surface water concentration (0.006 mg/L) previously reported.[2] If a participant reported using mixed water, we generally assumed a mixing ratio of 1:1 (Manjira to bore water). We assumed that all government-provided water was mixed, unless a participant reported using Manjira and bore water separately. In such cases, we assumed that only the Manjira water portion was mixed. We further assumed that water consumed outside the home was mixed if the consumption location was Patancheru, and the reported water source if otherwise. For our point estimates of health risk, we used the mean mixed water arsenic concentration of 0.3 mg/L. Some participants reported washing and cooking rice with water from different sources. We chose the source used to cook rice when estimating arsenic intake.

Risk Assessment - Point Estimates

We estimated daily and lifetime arsenic dose for each participant using the following equations[14]:

Average daily dose (ADD) (mg/kg-day) = IR / BW (4)

Lifetime average daily dose (LADD) (mg/kg-day) = IR x ED / BW x AT (5)

where:

IR = daily intake of arsenic from water (mg/day) (Equation 1)

BW= body weight (kg) from exposure questionnaire

ED = exposure duration (years)

AT = averaging time (i.e., either the USEPA default value of 70 years or the Indian average life expectancy [men = 61 years; women = 63 years][17]

To estimate non-cancer health risks, we calculated hazard quotients using the following equation[14]:

Hazard Quotient = ADD / RfD (6)

where:

ADD = average daily dose (Equation 5)

RfD = 0.0003 mg/kg-day —the oral reference dose for non-cancer health effects of arsenic.[18]

USEPA claims that a hazard quotient >1 indicates potential non-cancer health risks.[19] USEPA also notes that the hazard quotient is unlikely to be proportional to risk, but we used it nonetheless to qualitatively compare potential non-cancer risks for men versus women.[19]

We calculated excess cancer risks using the following equation[14]:

Excess cancer risk (per mg/kg-day) = LADD × CSF (7)

where:

LADD = lifetime average daily dose (Equation 5)

Figure 1

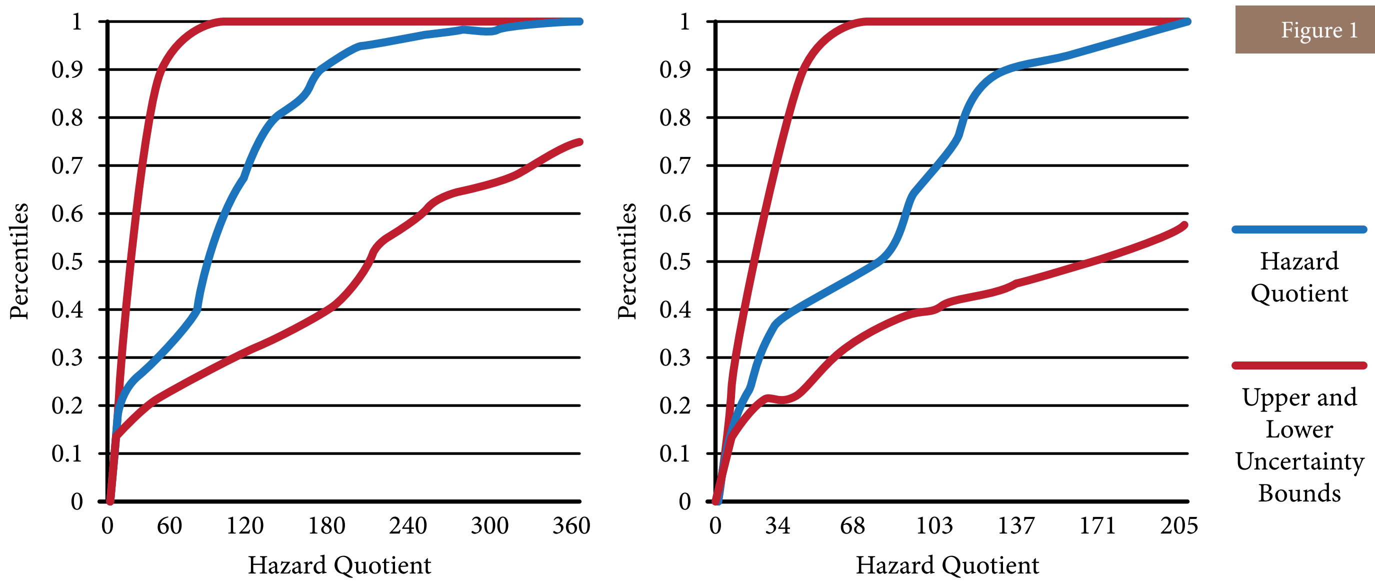

Figure 2

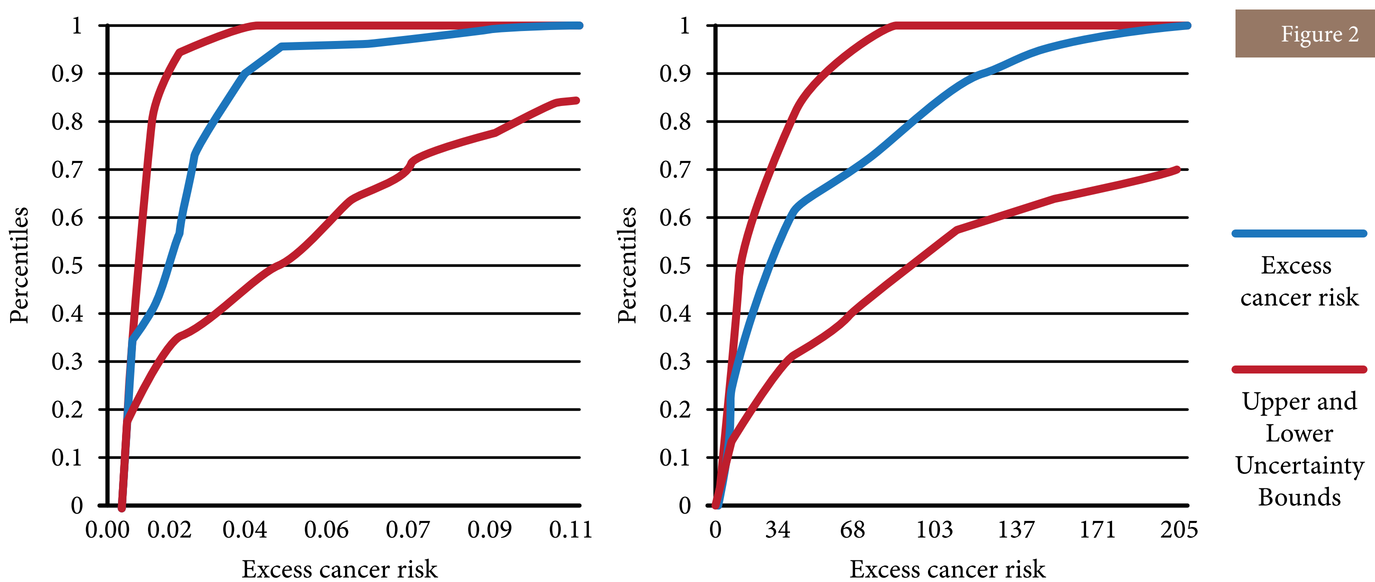

Figure 1 — Cumulative distribution of simulated hazard quotients for Bandlaguda men (left plot) and women (right plot) (blue line denotes the mean hazard quotient after 1,000 simulations; red lines denote lower and upper uncertainty bounds).
Figure 2 — Cumulative distribution of simulated excess cancer risk for Bandlaguda men (left plot) and women (right plot) assuming a 70-year life expectancy (blue line denotes the mean excess cancer risk after 1,000 simulations; red lines denote lower and upper uncertainty bounds).

CSF = 1.5 per mg/kg-day—the cancer slope factor (CSF) for oral ingestion of arsenic.[18]

Point estimates of hazard quotients and excess cancer risks were calculated for men and women separately. Two cancer risks were calculated for each participant: one using USEPA's default 70-year life expectancy, the other using the Indian life expectancy.

Risk Assessment - Probabilistic Estimates

We utilized the above equations and @RISK software (Palisade, Ithaca, NY) to produce probabilistic distributions of risk estimates for our study population. For many of the input variables (e.g., drinking water consumption, body weight, etc.), we fit empirical distributions using our questionnaire data. For others, we constructed distributions using the Define Distribution option in @RISK. USEPA has assigned an uncertainty factor of 3 to the arsenic oral RfD.[18] We adopted 3 as the uncertainty factor for both the RfD and CSF. We assumed uniform distributions for the RfD and CSF, with 0.0001 representing the minimum value and 0.0009 representing the maximum value for the RfD, and with 0.5 representing the minimum value and 4.5 representing the maximum value for the CSF (Devine 2010, personal communication with A. Pokkamthanam). We also constructed a uniform distribution for mixed water arsenic concentrations, with a minimum value representing a 1:9 mixing proportion (bore to Manjira water) and a maximum value representing a 9:1 mixing proportion (Devine 2010, personal communication with A. Pokkamthanam). The distribution of bore water arsenic concentrations was fit empirically using the 6 values selected from previous studies.[2] We did not fit distributions for averaging time/life expectancy or Manjira water arsenic concentration because we only had one value for each of these variables.

We applied the Latin Hypercube sampling algorithm in @RISK to conduct 1,000 iterations of our hazard quotient and excess cancer risk models. We used Excel to calculate the 5th-100th percentiles of the distributions of the mean estimates for men and women. We then plotted cumulative density functions (CDFs) of the mean risk estimates, as well as their lower and upper uncertainty bounds, which we calculated as the 5th and 95th percentiles, respectively, of each percentile estimate.

Variable	n	mean	standard deviation	median	min	max
Age						
Male	50	38.0	14.1	37.0	19	68
Female	50	36.3	12.7	35.0	19	68
Height (in.)						
Male	50	64.6	3.2	64.0	59	73
Female	50	59.9	2.9	60.0	56	68
Weight (kg)						
Male	50	58.8	8.7	57.0	43	81
Female	50	55.3	14.1	50.5	35	96
Income (Rs.)	96	76,509.4	67,876.0	52,200.2	0	420,000
Years lived in Bandlaguda	100	21.5	11.5	20.0	0	58
# of adults in household	100	3.6	1.8	3.0	2	10
# of children in household	100	1.7	1.3	2.0	0	7

Table 1a — Demographic characteristics of study population

We conducted sensitivity analyses in @RISK to evaluate the relative importance of each input variable to the simulated risk estimates. Tornado plots and mapped values were generated using the Simulation Sensitivities option. Tornado plots rank the importance of each variable to the risk estimates using regression coefficients. Mapped values quantify the change in estimate given a one standard deviation change in each variable.

Results

Overall, 157 households were visited to reach our goal of 100 study participants. Of the 57 excluded homes, 68% were not eligible or no one was home at the time of visit, 26% refused to be interviewed, and explanations were missing for 5%.

Tables 1a and *1b* show selected demographic and exposure characteristics. Generally, the men were older, taller, and weighed slightly more than the women in our study population. 78% of participants reported having attended school. The mean reported annual household income was 76,510 (±67,876) Rs.

All respondents reported having access to government-supplied bore water. 66% reported access to Manjira water, with half of these describing the panchayat as the supplier and the other half naming the Manjira Water Board (35%), Pennar Industry (12%), and suppliers/self (3%). 13% reported access to a third source, mainly well water, although none reported using a third source in the previous 24 hours, so we did not include these sources in our intake calculations. 33% reported keeping panchayat-provided Manjira water separate from bore water, believing that the government-supplied water, although sometimes mixed, was of better quality than the bore water available to them (details provided in the Supplemental Material). Eight participants reported using bottled water.

The mean total reported water consumption was 4.5 (± 2.4) L/day. Men and women differed significantly in terms of plain drinking water consumption, with mean consumption

Variable	Frequency (percent)
Ever attended school?	
No	22 (22)
Literacy (read and write well)	
No	32 (32)
Occupation (Work in the past 7 days)	
At home (includes housewives)	42 (43)
Work location (Work in the past 7 days)	
Bandlaguda (includes housewives)	73 (74)
Pregnant or lactating	
Lactating	8

Table 1b — Demographic characteristics of study population

Variable	n	mean	standard deviation	median	min	max
Total water consumption	100	4.5	2.4	4.0	0.1	13.2
Total non-government provided Manjira water consumption	46	3.8	2.6	3.3	0.3	10.4
Total government provided Manjira water consumption	33	3.3	2.4	3.0	0.1	10.5
Total wore water consumption	53	2.6	2.4	1.9	0.02	10.7
Total mixed water (as reported) consumption	14	2.0	2.0	1.3	0.1	6.6

Table 2 — Reported water consumption (L/day) by source

of 4.8 (± 2.5) L/day for males and 3.3 (± 1.6) L/day for females (details provided in the Supplemental Material). Seven reported drinking water consumption values were notably high (e.g. ≥ 10 L/day). We did not exclude these observations because we thought the estimates were plausible given high temperatures in July and the physically demanding nature of the participants' occupations (e.g., factory worker, laborer, welder, carpenter, farmer).[20] *Table 2* presents total water consumption by source. Additional data on consumption and sources of water used are provided in the Supplemental Material. Arsenic intake from Manjira water ranged from 0.001-0.1 mg/day, from mixed water 0.01-2.7 mg/day, and from bore water 0.01-5.4 mg/day. The mean arsenic intake from all water sources was 1.06 (±1.05) mg/day.

Risk Estimates

Our point risk estimates (*Table 3*) indicate that both non-cancer and cancer outcomes may be a concern for Bandlaguda men and women. Mean hazard quotients for men and women in our study population were 72 (±73) and 56 (±40), respectively. Mean lifetime excess cancer risks using the USEPA 70-year life expectancy were 0.01 (±0.02) (i.e., a 1 in 100 chance of developing cancer over a lifetime) for men, and 0.006 (±0.008) (i.e., 6 in 1,000) for women. Mean lifetime excess cancer risks using Indian life expectancies were 0.01 (±0.02) for men and 0.007 (±0.009) for women.

Figure 1 presents CDFs of the mean simulated hazard quotients for men (left plot) and women (right plot). The 95th percentiles of the mean simulated hazard quotients for men and women were 200 (54-610, uncertainty bounds) and 170 (44-540, uncertainty bounds), respectively. The uncertainty bounds contain the 95th percentile point estimates for both men and women.

The 95th percentile of the mean simulated excess cancer risk for men was 0.04 (0.02-0.17) using USEPA's 70-year life expectancy (*Figure 2*, left plot) and 0.05 (0.02-0.19) using the Indian life expectancy (not shown). For women, the 95th percentile was 0.03 (0.01-0.11) using the USEPA life expectancy (*Figure 2*, right plot) and 0.03 (0.01-0.12) using the Indian life expectancy (not shown). Additional results from the risk simulations are presented in the Supplemental Material.

Details on the sensitivity analyses are presented in the Supplemental Material. Briefly, the RfD was the most influential variable for the non-cancer risk estimates for both men and women. For every one standard deviation increase in RfD, the hazard quotient decreased by 0.01 for men and 0.89 for women. The CSF was the most influential variable for the cancer risk estimates. For men, for every one standard deviation increase in CSF, the excess risk increased by 0.03 using EPA's life expectancy and 0.04 using the Indian life expectancy. For women, each one standard deviation increase in CSF increased excess risk by 0.02 using USEPA's life expectancy and by 0.02 using India's life expectancy.

Discussion

We attempted to quantify potential health risks associated with consumption of arsenic-contaminated water by Bandlaguda adults. Our estimates show that Bandlaguda men may be at higher risk than women for both non-cancer and cancer outcomes. Multiple studies report associations between arsenicosis, skin cancer, and other arsenic-related diagnoses and groundwater concentrations.[2,21-23] Other researchers have performed risk assessments similar to ours in Taiwan and Viet Nam, finding elevated non-cancer and cancer risks despite using lower water consumption rates and arsenic concentrations than we did (details in Supplemental Material).[24,25]

Several sources of uncertainty affect our estimates. Recall bias likely influenced our participants' reported water consumption, but the direction of bias is not readily apparent. An evaluation of differences between self-reported 24-hour water consumption and consumption rates from interviews among 19 Bangladeshi men and women in September 2002 found results to be similar.[26] The mean and maximum water intakes were 3 and 6 L/day, respectively— slightly lower than those reported by our participants.

Additionally, there is uncertainty associated with the amount of water that men in our study used to make mixed drinks and food, since men generally do not perform these tasks in Bandlaguda. We learned anecdotally that Bandlaguda residents generally use a 1:1 proportion of milk and water to make mixed drinks like coffee and tea and used this in our analyses. We also used proxy measures of water used in cooking for both men and women.

Our use of older arsenic data adds[2] uncertainty to our results, although its been suggested that arsenic concentrations in most wells remain unchanged over time.[27] If the number and types of arsenic pollution sources in Bandlaguda changed substantially in recent years, however, then more up-to-date data would be needed. Further, arsenic concentrations vary with well depth[28-30]; bore well depth in Bandlaguda ranged from 50-75m.[2] There is also uncertainty associated with our mapping exercise, since the map used did not provide coordinates for each well sampled.[2] According to this map, the highest arsenic concentration (1.3 mg/L) was measured from a well inside Bandlaguda, but we are not certain if our study participants actually used this well. We also assumed the arsenic concentration of Manjira water to be the lowest (0.006 mg/L) detected in surface water, but we cannot be sure that Manjira water is actually treated to this level.[2] Last, we assumed a 1:1 mixing proportion of Manjira-to-bore water in water participants reported as mixed but actual mixing ratios are likely to vary.

Uncertainty in our cancer risk estimates also stems from the assumption that arsenic concentrations and water consumption habits remain constant over a person's lifetime. In reality, water sources and consumption habits are likely to change, but we did not measure this. Finally, the RfD and CSF were the most influential input variables in our sensitivity analyses, yet the USEPA values we used have their own associated uncertainties.[18]

Conclusion

Our results illustrate potential non-cancer and cancer risks associated with ingestion of arsenic-contaminated water in Bandlaguda and thus the urgent need for affordable, energy-efficient filtration options to ensure safe drinking water for this and similar communities. Additional site-specific research would help to more accurately characterize the important variables driving our risk calculations. For example, a comprehensive survey of arsenic concentrations in the water actually consumed by residents would help reduce uncertainty in the ADD/LADD estimates. Likewise, because food may be an important source of arsenic exposure,[7] a more comprehensive evaluation of arsenic levels in rice and dal may also be useful. Researching occupational exposure to arsenic may also be important, as many Bandlaguda men work in nearby industries. In the immediate-term, local health and environmental officials should consider a campaign to identify bore wells with arsenic concentrations exceeding the Indian drinking water standards and educate community members on the hazards of drinking water from these wells.

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Risk Estimate	mean	standard deviation	median	max	95th percentile estimate
Hazard quotient					
Males	72	73	0.1	370	180
Females	56	40	0.6	210	160
Excess cancer risk (using EPA 70-year life expectancy)					
Males	0.01	0.02	0.00003	0.1	0.04
Females	0.006	0.008	0.00005	0.04	0.02
Excess cancer risk (using Indian average life expectancy)					
Males	0.01	0.02	0.00004	0.1	0.04
Females	0.07	0.009	0.00006	0.03	0.02

Table 3. Point estimates of non-cancer and cancer risk association with oral ingestion of arsenic-contaminated water among Bandlaguda adults

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