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ORIGINAL RESEARCH

Estimating the Prevalence of Toxic Waste Sites in Low- and Middle-Income Countries

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Abstract

BACKGROUND Exposure to heavy metals at contaminated industrial and mining sites, known also as hot spots, is a significant source of toxic exposure and adverse health outcomes in countries around the world. The Toxic Sites Identification Program (TSIP) developed by Pure Earth, a New York—based nongovernmental organization, is the only systematic effort to catalogue contaminated sites globally. To date, TSIP has identified and catalogued 3282 sites in low- and middle-income countries. The TSIP methodology is not designed to survey all contaminated sites in a country. Rather sites are prioritized based on their perceived impact on human health, and only a limited number of the most highly hazardous sites are surveyed. The total number of contaminated sites globally and the fraction of contaminated sites captured by TSIP is not known.

OBJECTIVE To determine the TSIP site capture rate, the fraction of contaminated sites in a country catalogued by TSIP.

METHODS Ghana was selected for this analysis because it is a rapidly industrializing lower middle income country with a heterogeneous industrial base, a highly urban population (51%), and good public records systems. To develop an estimate of the fraction of sites in Ghana captured by TSIP, assessors targeted randomly selected geographic quadrats for comprehensive assessment using area and population statistics from the Ghana Statistical Service. Investigators physically walked all accessible streets in each quadrat to visually identify all sites. Visual identification was supplemented by field-based confirmation with portable x-ray fluorescence instruments to test soils for metals. To extrapolate from survey findings to develop a range of estimates for the entire country, the investigators used 2 methodologies: a “bottom-up” approach that first estimated the number of waste sites in each region and then summed these regional subtotals to develop a total national estimate; and a “top-down” method that estimated the total number of sites in Ghana and then allocated these sites to each region. Both methods used cluster random sampling principles.

FINDINGS The investigators identified 72 sites in the sampled quadrats. Extrapolating from these findings to the entire country, the first methodology estimated that there are 1561 sites contaminated by heavy metals in Ghana (confidence interval [CI]: 1134-1987), whereas the second estimated 1944 sites (CI: 812-3075). The estimated total number of contaminated sites in Ghana is thus 7-9 times the number of sites captured through TSIP. On a population basis, it was estimated that there are between 31 and 115 contaminated sites per million inhabitants in Ghana.

CONCLUSIONS The findings of this study indicate that the TSIP methodology provides a sound statistical basis for policy formulation. The statistical approaches used in this study can be replicated in other countries to improve estimates of the prevalence of contaminated sites. This information provides

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important input to calculations of the global burden of disease attributable to hazardous exposures at contaminated sites.

KEY WORDS contaminated sites, pollution, global burden of disease, heavy metals, field survey, Toxic Sites Identification Program (TSIP)

INTRODUCTION

Pollution is critically linked to poverty and produces disproportionate health effects on low-income communities worldwide.[1] On a global scale, low- and middle-income countries face barriers to infrastructural and inclusive economic development as a result of challenges borne from pollution and associated environmental health issues.[2,3] Rapid industrialization, population growth, and exploitation of natural resources have potentially resulted in significant environmental degradation in many low- and middle-income countries (LMICs).[4] These countries often have limited governmental capacity and few incentives to formally regulate environmentally damaging industries or address contaminated sites. Even in cases where regulations exist, the capacity to manage or enforce laws can be limited.

Contamination by toxic chemicals and heavy metals presents a unique and ongoing problem. Adverse health effects from chemical contamination, through processes such as informal lead-acid battery recycling, natural resource extraction, and electronic waste recovery and disposal, often go unnoticed in part because of the latency and chronic nature of environmental toxicants.[5,6] Limited regulatory policies as well as the ubiquity of small-scale informal practices make identifying active and legacy contaminated sites a challenge for intervening policy and health care professionals.

Lack of best practices in unregulated and small-scale industries often leads to an increased risk of exposure to toxicants. Artisanal small-scale gold (ASGM) mining, for example, typically involves panning gold-containing alluvial soils or crushed ores with elemental mercury (Hg). This mercury-gold amalgam is then heated, which drives off the mercury as a vapor and leaves behind both gold and some residual mercury.[7] Large amounts of Hg vapor recondense and deposit locally and can be re-emitted from water and soil surfaces or can be methylated, bioaccumulate, and biomagnify in food chains.[8,9] Surface soils, water bodies, and sediments are the major biospheric sinks for Hg.[10] In short, artisanal gold mining using elemental mercury poses a significant risk to human health because mercury is a potent neurotoxin and systemic toxin.[11]

In addition to mercury, other metals, including lead (Pb), cadmium, hexavalent chromium, cobalt, and manganese resulting from informal industry can be hazardous to human health. Lead exposure, for example, can lead to cognitive impairment, anemia, hypertension, kidney damage, and, in extreme cases, death.[12] Historically, the source of lead exposure is often traced to gasoline, paint, air, water, interior dust, soil, and food.[13] In areas within the vicinity of mining and industrial establishments, ingestion of soil and dust contaminated with heavy metals is a primary source of lead exposure.[14,15] Lead can also be ingested via drinking water when soluble forms are present in surface or groundwater.[16]

Epidemics of metal poisoning resulting from informal industry have been documented in multiple LMICs, including Senegal, Ghana, Indonesia, and the Philippines.[17-20] A particularly severe case was the recent (2010) tragedy in the Nigerian state of Zamfara resulting from ASGM with lead-laden ore.[21] Acute pediatric exposures there resulted in the deaths of at least 400 children, nearly 25% of who were younger than age 5.[22,23] Two-thirds of households reported processing lead-contaminated gold ore inside family compounds. Soil lead levels in 85% of family compounds exceeded the US Environmental Protection Agency (EPA) action level for areas of bare soil where children play (400 mg/kg).[24]

Despite the significant health burden posed by informal industry, little documentation of sites and exposures exists. Several factors likely inhibit programs, including a lack of available government resources in LMICs and a possible institutional reluctance to identify a Pandora's box of problems that can be difficult to resolve.[25]

The only systematic effort to catalogue contaminated sites globally is the Toxic Sites Identification Program (TSIP) developed by Pure Earth, a New York–based nongovernmental organization.[1] TSIP uses a rapid risk assessment tool modeled after the EPA's Hazard Ranking System.[26] The protocol, the Initial Site Screening (ISS), requires a site visit and sample collection and relies on the source-pathway-receptor model. The EPA uses a similar, albeit more robust, model to assess contaminated sites in the United States. The EPA Hazard Ranking System requires additional information on spatial attenuation, pollutant persistence, migration potential, and likelihood of future release. By contrast the ISS is indented to be implemented quickly and at low cost. As of December 2015, 3282 waste sites had been identified globally. Of those, an ISS was carried out at 2434 sites in 51 countries. Contaminated sites are identified through several methods, including knowledge and expertise of local staff, investigation of previously identified legacy sites, collaboration with local governments or research organizations, and online nominations. Once a site has been identified, a specially trained investigator conducts an ISS. The completed ISS is entered into an online database and reviewed by the New York office for quality assurance and control.

The TSIP effort has been useful for documenting hazardous waste sites, though it has been somewhat limited by time and resources. As a result, likely only a fraction of the total eligible sites in a given country are being captured. Moreover, the TSIP program likely suffers from selective inclusion and may not be an accurate representation of the distribution of waste sites in any particular country because it is not designed to survey all contaminated sites in a country. Rather sites are prioritized based on their perceived impact on human health, and only a limited number of the most highly hazardous sites are surveyed in each country. Sites are selected through interviews with relevant government agencies, academics, and local leaders.

We undertook the present study to assess the TSIP capture rate, the fraction of all contaminated sites in the country catalogued in TSIP. The West African country of Ghana was selected for the study because of a partnership between Pure Earth and a highly qualified nongovernmental organization in Ghana and a strong relationship with both the Ghana Environmental Protection Agency and Ghana Health Service. Additionally, Ghana regularly collects data and has good public records systems.

Ghana (area 238,535 km^2) is a lower middle income country that is home to 26.8 million residents.[27] The population density is highest in the southern half of the country, where urban centers such as Kumasi and Accra attract more economic opportunities than the rural areas of the north. Chemical production and metals smelting and processing are among the largest contributors to the formal industrial economy. Automotive battery recycling, ASGM using mercury, and scrap metal and electronic waste recycling are the most abundant industries of the informal sector.[28,29]

METHODS

The statistical approaches used in this study seek to estimate the total number of heavy metals contaminated sites throughout Ghana. This estimate is then compared with the number of sites currently catalogued in the TSIP database to obtain a capture rate.

This study makes use of the site identification protocol designed under TSIP to focus on site assessments throughout Ghana's administrative districts. Given that the majority of waste sites in TSIP involve heavy metals such as Hg, lead, chromium, and cadmium, this study focused on estimating sites containing heavy metal contamination.

This study used 2 surrogate methodologies to estimate the total number of heavy metals contaminated waste sites in Ghana. Although individual cases of heavy metal polluting industries within Ghana are well documented (eg, small-scale gold mining and used lead-acid battery recycling), research on the countrywide extent of pollution and potential number of contaminated sites is deficient. Surrogate methods were used because of a lack of resources, limited amount of data, and no clearly appropriate methodology for extrapolating the data to the country. For these reasons, we pursued 2 methodologies in our extrapolation.

The first method (Regional) estimated the regional number of waste sites first and then summed to find a total in Ghana within a particular confidence interval. The second method (Countrywide) estimated the total number of sites in Ghana, then "allocated" them to each region. Both methods use cluster random sampling analytical principles in determining the estimated number of waste sites.

Although this methodology is well known, this is the first instance where it has been applied to waste site estimation.[30]

District Selection, Site Screening, and Inclusion of Toxicants. Ghana is divided into 10 regions that are further subdivided into 216 administrative districts. Two regions, Upper East and Upper West, each represent less than 5% of the country's total population and were not included in data collection. One district from each of the remaining 8 regions was randomly selected for inclusion in the study. The information collected from each district was then used to estimate the number of toxic sites found per region and for the country as a whole. The following 8 districts were randomly selected for inclusion into this study: Amansie West, Tano South, Abura/Asebu/Kwamankese, Afram Plains South, Ningo Prampram, Yendi, Ho, and Juabeso. Districts selected for screening are highlighted in Figure 1.

All population and area data were collected from the Ghana Statistical Service (GSS).[31] GSS conducts censuses every 10 years and presents data in aggregate level by district and region. The data is freely available online.

An onsite waste site identification protocol based on visual assessment was established to effectively identify contaminated sites. Although this methodology targets the sampling in place of randomized techniques, it is important to note the unique conditions in which most toxic sites emerge. Informal mining and recycling of metals and scraps often occur with little regulatory oversight from the government in low-income areas and informal settlements. In addition, legacy sites in industrial centers that pose no risk to human health can stand for long periods without risk management. Randomly sampling throughout a district to confirm toxic site status is not time or cost effective because certain areas such as high-income residential neighborhoods would produce few sites if any. Additionally, randomly sampling in areas where populations are not exposed would not reveal sites within our scope. The visible site identification protocol was developed with these conditions in mind.

The protocol defined 2 levels of toxic site identifiers: primary and secondary. The identifiers were given a scoring rubric including 2 points for primary identifiers and 1 point for secondary identifiers. In order to assess a potentially toxic site, investigators were instructed to review all available identifiers and only begin site assessment on achieving a minimum required score of 6. Site assessments used x-ray fluorescence spectrometry (Innov-x Systems Alpha Series 6500 Handheld XRF Analyzer) to evaluate the level of contamination of various heavy metals.

The list of primary identifiers was composed of the following: documentation of abandoned or legacy site status (ie, confirmed by community or public records), tailings piles, visible particle emissions, and confirmed industry activity. Confirmed industry activity for the purposes of this study could be an active or legacy site used for mining or ore processing, battery recycling, chemical manufacturing, dye industry, electronic waste recycling, heavy industry, industrial or municipal dumpsites, lead mines, lead smelting, pesticide manufacturing, petrochemical industries, product manufacturing, recycling, ship breaking, or tannery operations. The list of secondary identifiers was composed of the following: visibly stressed vegetation, mechanical tools or supplies (including baghouses and filtering equipment), industrial equipment in disrepair, organic olfactory clues, petroleum or other stained soil, and visibly discolored surface water or puddles.

A local team of trained environmental site investigators was assigned to locate and assess various potentially toxic sites throughout the 8 administrative districts. Trained site investigators obtained street maps for each district and worked with local officials to strategize and plan the most effective route for mapping. Individual towns, villages, and neighborhoods were targeted. Highways and main roads between populated areas were overlooked. The purpose of the exercise was to assess contaminated sites that had an apparent pathway for human exposure.

Estimates of the number of sites found per district within these regions were determined after data collection. Statistical analysis was performed with variance and a 95% confidence interval determined for the mean number of toxic sites per district sampled. Standard statistical techniques were used to extrapolate the mean and variance of the sample to the entire country of Ghana.

Although statistical analysis relies on random sampling techniques, the sampling was targeted, which has likely biased our estimates of the number of toxic sites in Ghana away from zero. The size of this bias is difficult to ascertain, but we have chosen this methodology to include the widest possible corridor in our 95% confidence interval to reflect both the variation in the sampling results and the uncertainty regarding the assumption of independence between the samples.

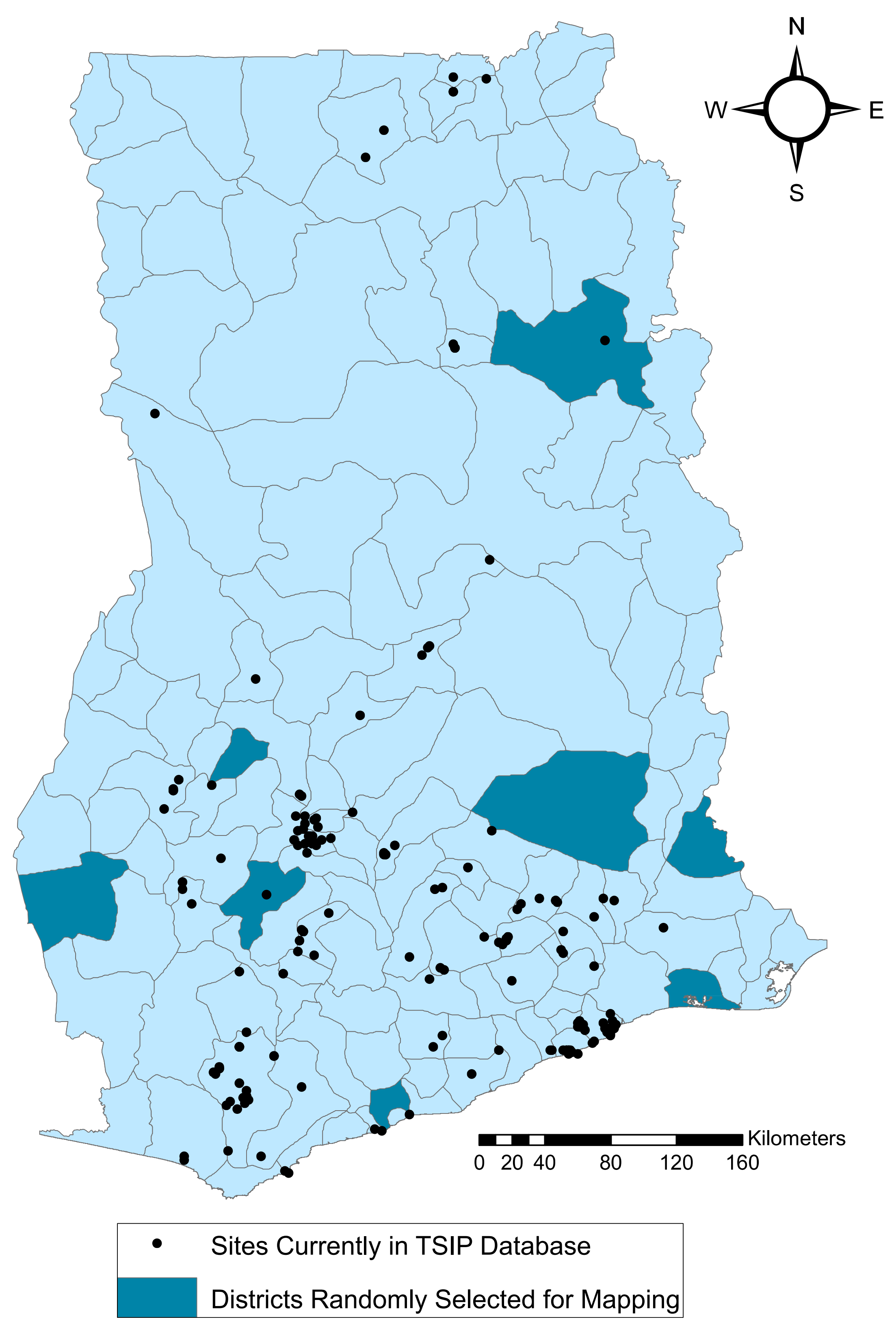

Figure 1. Map of Ghana. Abbreviations: TSIP, Toxic Sites Identification Program.

The collected data set was truncated to include only sites where the key pollutant was a heavy metal with credible health impacts and sites where the level of contamination exceeded US EPA standards or equivalent for exposure. Raw data were compared against US EPA standards 3 times to ensure quality control. These criteria narrowed the focus of the dataset to include the toxicants lead, chromium, arsenic, cobalt, and manganese at concentrations that would pose a threat to human health. The 5 heavy metals are each heavily cited in the literature as causing adverse health effects from exposure and intake at relatively low quantities. Mercury, also a key toxicant, was not included in the final data capture because of measuring limitations in the equipment used. The focus on heavy metals also limits the scope of the analysis. Therefore, the results are not an estimate of all contamination countrywide, but rather an estimate solely of heavy metals contamination.

$$T = u + v$$

$$\text{where } u = \frac{1}{2}\left[\sum_{i=1}^{N}\left(\frac{x_i}{Area\ Dst_i}\right) \times Area\ Rgn_i + \sum_{i=1}^{N}\left(\frac{x_i}{Pop\ Dst_i}\right) \times Pop\ Rgn_i\right]$$

$$\text{and } v = \frac{1}{2}\left[\sum_{i=1}^{M}\left(Avg\ Sites\ Per\ Area\ Sampled\right) \times Area\ Rgn_i + \sum_{i=1}^{M}\left(Avg\ Sites\ Per\ Pop\ Sampled\right) \times Pop\ Rgn_i\right]$$

Regional Analysis Methodology. In this approach, the data collected in the 8 randomly chosen districts were extrapolated to estimate the number of toxic sites per region using regional characteristics of area and population. Site estimates by area were calculated using the number of sites found in a sampled district *(x_i)* divided by the total area of the district *($Area\ Dst_i$)* and then multiplied by the total area of the region to which the district belongs *($Area\ Rgn_i$)*. Estimates based on population were calculated in the same manner. The 2 results were averaged to estimate the number of toxic sites expected in each region; see the formula for *u* later. Table 1 contains information for area and population statistics by region.

Because of budgetary and time constraints, 2 regions of Ghana were not sampled and were selected for exclusion by population weighting. The number of contaminated sites in these regions was estimated using data collected and described earlier for the 8 mapped and sampled regions. An average number of toxic sites in the sampled area of Ghana was found by area and population. These averages were assumed to apply proportionally to the unsampled regions. The area and population-based results were then averaged to estimate the number of toxic sites expected in each region; see the formula for *v* later.

A total estimate of toxic sites countrywide *(T)* is equal to the sum of the sampled and not sampled extrapolations. A 95% confidence interval around this estimate was determined using techniques applicable to cluster random sampling, treating each region as a cluster.

Regional Calculation Formulas

where

T is the total estimate of toxic sites countrywide.
u is the sampled district extrapolation.
v is the not sampled district extrapolation.
x_i is the number of sites found in district i.
N is the number of regions sampled.
M is the number of regions not sampled.
$Area\ Dst_i$ is the area of district i.
$Area\ Rgn_i$ is the area of region i.
$Pop\ Dst_i$ is the population of district i.
$Pop\ Rgn_i$ is the population of region i.

Countrywide Analysis Methodology. A second analysis estimated the total number of toxic sites in Ghana assuming the randomly selected districts where toxic site analysis was performed were a representative sampling of districts in Ghana. The total number of sites in the county was then determined to be the average number of sites found in sampled districts ($\overline{x}$) multiplied by the number of districts in Ghana *(b)*; see the formula for *T* below. The 95% confidence interval around this estimate was also determined assuming random sampling techniques.

From this total estimate, the number of toxic sites per region *(R_i)* was estimated using an equally weighted measure of 3 categories: number of sites found in the region, area of the region, and population of the region; see the formula for R_i later.

Countrywide Calculation Formula

$$T = \bar{x} \times b = \sum_{i=1}^{P} R_i$$

$$\text{where } R_i = \frac{T}{3}\left[\left(\frac{x_i}{\sum_{i=1}^{N} x_i}\right) + \left(\frac{Area\ Rgn_i}{Total\ \ Country\ \ Area}\right) + \left(\frac{Pop\ Rgn_i}{Total\ \ Country\ \ Pop}\right)\right]$$

where

T is the total estimate of toxic sites countrywide.

N is the number of regions sampled.

$\bar{x}$ is the average number of sites found in sampled districts.

R_i is the estimated number of contaminated sites in region i.

x_i is the number of sites found in district i.

b is the number of districts.

P is the total number of regions.

RESULTS

The team conducted data analyses between July and August 2015. In total, 72 toxic sites were confirmed (Table 2). For the purpose of this study, a confirmed toxic site was defined as having a soil sample containing one of the predefined heavy metals at a concentration above US EPA standards (or equivalent) through instrumental XRF analysis. The breakdown of contaminated sites by pollutant can be seen in Figure 2. The geometric mean (GM) lead level of the samples taken at sites classified as contaminated was 2723 ppm (n = 27); the US EPA action level for lead in residential soil is 400 ppm. The highest lead reading in a mixed-use industrial/residential area was 97,835 ppm—more than 244 times the residential standard and 81 times the industrial standard. The GM of chromium samples taken at contaminated sites was 628 ppm (n = 20). The highest chromium sample recorded in the study was 4216 ppm—more than 19 times the residential standard of 220 ppm. The GM of arsenic samples taken at contaminated sites was 101 ppm (n = 16). The highest sample recorded was 5661 ppm—more than 470 times the standard of 12 ppm arsenic in either residential or industrial soil. Cobalt (n = 7) and manganese (n = 2) samples had geometric means of 846 ppm and 687 ppm, respectively.

Results Using Regional Analysis Methodology. Analysis using the Regional Analysis technique (bottom-up approach) for toxic site assessment yielded 1521 and 1601 contaminated sites for estimates based on area (km^2) and population, respectively (Table 3). Assuming equal weighting, the mean number of contaminated sites was 1561 (95%

Table 1. Regional Characteristics and District Selection

Region	No. of Districts	Area (km^2)	Population (2010 census)	Population Weighting (%)	Population Density (persons/km^2)	No. of Districts Chosen
Ashanti	30	24,889	4,780,380	19.39	192.1	1
Brong-Ahafo	27	39,557	2,310,983	9.37	58.4	1
Greater Accra	16	3245	4,010,054	16.26	241.8	1
Central	20	9826	2,201,863	8.93	136.3	1
Eastern	26	19,323	2,633,154	10.68	1235.8	1
Northern	26	70,384	2,479,461	10.06	35.2	1
Western	22	23,921	2,376,021	9.64	103.0	1
Upper East	13	8842	1,046,545	4.24	99.3	0
Upper West	11	18,476	702,110	2.85	118.4	0
Volta	25	20,570	2,118,252	8.59	38.0	1
Total	**216**	**239,033**	**24,658,823**	**100**	—	**8**

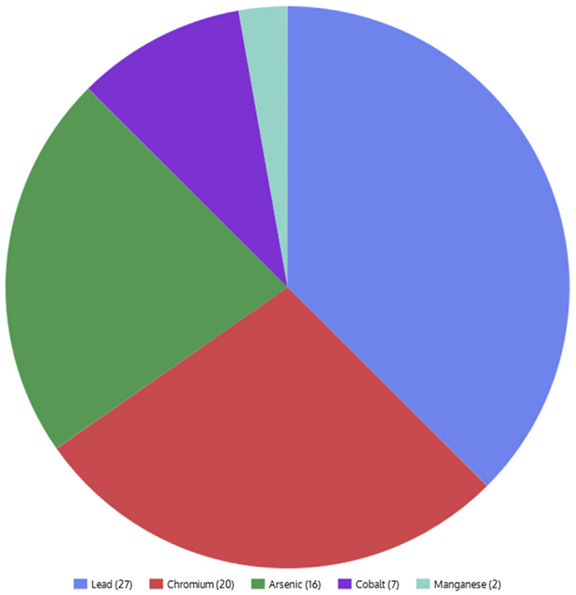

Figure 2. **Key pollutants at confirmed contaminated sites.**

confidence interval [CI]: 1135-1987), with a range of sites between 8 and 311 per region.

Results Using Countrywide Analysis Methodology. The Countrywide Analysis technique (top-down approach) estimated 1944 existing contaminated sites (95% CI: 812-3075) in Ghana. At the regional level the range of estimated toxic sites is 51-444. The countrywide extrapolation statistics and number of site estimates per region can be found in Tables 4 and 5.

DISCUSSION

Significance of Results. The estimation and extrapolation techniques outlined in this study are a preliminary attempt to estimate the scale of heavy metals contaminated sites countrywide based on district-level data. Such estimation has not previously been reported. The current extrapolation indicates that there are between 1561 and 1944 heavy metal–contaminated sites in Ghana (CI 812-3075). The number of confirmed toxic waste sites in Ghana according to the 2015 TSIP database is 215. These estimates indicate that the total number of contaminated sites in Ghana is approximately 7 to 9 times the number of contaminated sites previously enumerated through the TSIP methodology. When including only those sites that are contaminated by lead, arsenic, chromium, cobalt, and manganese, the extrapolations reported by both methods are between 16 and 20 times the currently enumerated

Table 2. **Number of Contaminated Sites by District**

District	Area (km^2)	Population	Population Density (Inhabitants/km^2)	No. of Confirmed Contaminated Sites
Amansie West	1197	134,331	112.2	7
Tano South	699	78,129	111.7	7
Abura/Asebu/Kwamankese	368	117,185	318.4	6
Afram Plains South	4882	218,235	44.7	1
Ningo Prampram	1553	122,836	79.1	7
Yendi	4090	199,592	48.8	21
Ho	978	271,881	278.1	5
Juabeso	2050	111,749	54.5	18
Total	**72**			

Table 3. **Summed Regional Extrapolation (Methodology 1)***

Region	No. of Confirmed Contaminated Sites	Regional Extrapolation by Area	Regional Extrapolation by Population	Final Extrapolation (50% Area, 50% Population)
Ashanti	7	145.52	249.11	197
Brong-Ahafo	7	395.88	207.05	301
Greater Accra	6	160.19	121.65	141
Central	1	3.96	12.07	8
Eastern	7	14.63	228.52	122
Northern	21	361.38	260.88	311
Western	18	105.20	38.96	72
Upper East	0	209.99	382.72	296
Upper West	0	40.25	60.09	50
Volta	5	84.10	40.31	62
Total	**72**	**1521.10**	**1601.35**	**1561**

* Sample variance: 32,496; 95% confidence interval (CI; lower bound): 1135; 95% CI (upper bound): 1987.

number of sites in Ghana. Word of mouth and footwork are the most effective tools for toxic site identification.

This extrapolation offers insight into the potential number of sites contaminated by heavy metals nationwide in Ghana. Reliable toxic site estimates and potential exposure based on thorough data via targeted sampling could greatly improve environmental burden of disease estimates.[1] Sites identified via the TSIP protocol can help fill critical knowledge gaps and play an important role in policymaking.

Site identification efforts carried out through the Toxic Sites Identification Program remain a cost effective and technically simple yet sound way to identify and rank contaminated sites. Going forward, additional efforts should be made to verify the population basis estimates calculated in this study and determine country-specific capture rates and underestimation factors. Verifying and narrowing these estimates will greatly assist policymakers and practitioners of public health as they continue to address toxic sites and chemical exposures in low- and middle-income countries. In those countries where toxic site data is extremely limited or completely unavailable, completing a mapping exercise within a representative sample of quadrats using the methods outlined in this study has the potential to greatly inform health and environmental policy.

Ghana has made notable efforts in curtailing impacts from heavy metal exposures to both workers and the general population. The central government has banned lead in consumer paint and in 2003 successfully phased out lead in gasoline. In the same year, Ghana ratified the Basel Convention in support of controlling the transboundary movement of hazardous wastes and waste disposal. Yet, like many LMICs, ensuring capacity to address the scale of contamination problems requires policy enforcement, funding, and thorough transitioning to best practices where necessary. Information regarding existing numbers of toxic sites and estimated projections are useful in determining a stepwise plan toward further site identification and eventual mitigation. Such estimates are useful in prioritizing the limited remediation funds available from developmental organizations.

Study Limitations. Though the selection of districts where site assessments took place was randomized, sampling was not. Therefore, statistical techniques to estimate the country total are not based on simple random sampling, largely because of the time-consuming and costly nature of randomly

Table 4. **Countrywide Extrapolation (Methodology 2)**

Basis	Countrywide Extrapolation
Districts sampled	8.00
Mean sites per sample	9.00
Standard deviation of the samples	6.82
Standard error for mean	2.37
t table value (5%)	2.36
95% CI (lower)	3.39
95% CI (upper)	14.61
Total districts	216
Total sites estimated	1944
Variance of total	228,852
95% CI (lower bound)	812.8
95% CI (upper bound)	3075.2

CI, confidence interval.

Table 5. Regional Site Estimates From Countrywide Extrapolation (Methodology 2)*

Region	No. of Districts	Estimated Sites Weighting	Area Weighting (km^2)	Population Weighting	Weighted Regional Estimate
Ashanti	30	63	67	125	255.21
Brong-Ahafo	27	63	107	60	230.54
Central	20	54	27	62	142.64
Eastern	26	9	52	69	130.09
Greater Accra	16	63	9	105	176.44
Northern	26	189	191	65	444.51
Volta	25	45	56	55	156.04
Western	22	162	65	62	288.85
Upper East	13	0	24	27	51.28
Upper West	11	0	50	18	68.41
Total	**1,944.00**				

* Equal weights (33.333%) were given to each factor.

sampling throughout several thousand square kilometers. The lack of randomization likely biases the results slightly. However, because of the lack of such a methodology in the scientific published reports, there appears to be no “gold standard” for a method.

In addition, because of analytical limitations of the XRF sampling equipment, mercury, a highly toxic transition metal, was not included in the sampling analysis. The Agency for Toxic Substances and Disease Registry suggests a health safety limit of 1 ppm for elemental mercury; however, the sampling equipment was unable to detect mercury levels less than 15 ppm. Ghana’s rich gold ore deposits make small-scale mining a viable economic source for many low-income families. In 2013, the country’s total gold output stood at 97.8 tons.[32] One-third of Ghana’s annual gold production likely comes from the artisanal and small-scale industry and almost all gold is exported.[33] Presently there are 77 mercury-contaminated sites, largely the result of gold mining, in the TSIP database. If the same extrapolation found for heavy metals included in this study is applied to mercury sites, we estimate there are between 539 and 847 mercury-contaminated sites throughout the country. However, because of a lack of comprehensive identification and sampling within a representative section of the country, these values cannot be confirmed with any certainty. Had mercury sites been included in the assessment, the estimated number of toxic waste sites would have increased substantially.

CONCLUSIONS

Our current extrapolation indicates that there may be an estimated 1561-1944 heavy metal—contaminated sites in Ghana, excluding mercury-contaminated sites. This is approximately between 7 and 9 times the total number of contaminated sites in Ghana previously documented in the TSIP. On a population basis, it was estimated that there are between 31 and 115 contaminated sites per million inhabitants in Ghana.

Identification of contaminated sites allows health and environmental ministries to better allocate limited resources for improved health surveillance and remediation. Because of the costly and time-consuming nature of toxic site identification and analysis, contaminated site extrapolations prove to be a valuable tool. The statistical approaches used in this study can be replicated in other countries to better understand the prevalence of contaminated sites and formulate policy. Additional efforts should be made to verify the population basis estimates calculated in this study and determine country-specific capture rates and underestimation factors.

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REFERENCES

1. Zhou Z, Dionisio KL, Arku RE, et al. Household and community poverty, biomass use, and air pollution in Accra, Ghana. Proc Natl Acad Sci 2011;108:11028–33.
2. Furie GL, Balbus J. Global environmental health and sustainable development: the role at Rio+20. Ciência Saúde Coletiva 2012;17:1427–32.
3. Landrigan P, Fuller R. Environmental pollution: An enormous and invisible burden on health systems in low- and middle-income countries. World Hosp Health Serv 2014;50:35–40.
4. Alam S. Globalization, poverty and environmental degradation: sustainable development in Pakistan. J Sustainable Dev 2010;3:103–14.
5. Lee S, Na S. E-waste recycling systems and sound circulative economies in East Asia: a comparative analysis of systems in Japan, South Korea, China and Taiwan. Sustainability 2010;2:1632–44.
6. Loomis E. Outsourcing pollution. In: Out of Sight: The Long and Disturbing Story of Corporations Outsourcing Catastrophe. New York, NY: New Press; 2015.
7. Gibb H, O'Leary KG. Mercury exposure and health impacts among individuals in the artisanal and small-scale gold mining community: a comprehensive review. Environ Health Perspect 2014;2014(122):667.
8. United Nations Environment Programme (UNEP). Global Mercury Assessment 2013: Sources, Emissions, Releases and Environmental Transport. Geneva, Switzerland: UNEP; 2013.
9. US Environmental Protection Agency (EPA). Mercury Study Report to Congress Volume III: Fate and Transport of Mercury in the Environment. Washington, DC: EPA; 1997.
10. United Nations Environment Programme (UNEP). Global Mercury Assessment. Geneva, Switzerland: UNEP; 2002.
11. Basu N, Clarke E, Green A, et al. Integrated assessment of artisanal and small-scale gold mining in Ghana—part 1: human health review. Int J Environ Res Public Health 2015;12:5143–76.
12. US Environmental Protection Agency (EPA). Children Are Not Little Adults. Washington, DC: EPA. Available at: http://www2.epa.gov/children/children-are-not-little-adults; 2015. Accessed December 9, 2015.
13. World Health Organization. Lead Poisoning and Health. Geneva, Switzerland: World Health Organization. Available at: http://www.who.int/mediacentre/factsheets/fs379/en; 2015. Accessed December 9, 2015.
14. Lanphear BP, Matte TD, Rogers J, et al. The contribution of lead-contaminated house dust and residential soil to children's blood lead levels: a pooled analysis of 12 epidemiologic studies. Environ Res 2013;79:51–68.
15. Kwame Aboh IJ, Sampson MA, Nyaab LA, et al. Assessing levels of lead contamination in soil and predicting pediatric blood lead levels in Tema, Ghana. J Health Pollution 2013;3:7–12.
16. US Centers for Disease Control. Potential for human exposure. In: Tox Profiles. Atlanta, GA: Agency for Toxic Substances and Disease Registry, US Centers for Disease Control:329–31. Available at: http://www.atsdr.cdc.gov/toxprofiles/tp13-c6.pdf; 2015. Accessed December 9, 2015.
17. Haefliger P, Mathieu-Nolf M, Lociciro S, et al. Mass lead intoxication from informal used lead-acid battery recycling in Dakar, Senegal. Environ Health Perspect 2009;117:1535–40.
18. Ntow WJ, Tagoe LM, Drechsel P, Kelderman P, Nyarko E, Gijzen HJ. Occupational exposure to pesticides: blood cholinesterase activity in a farming community in Ghana. Arch Environ Contam Toxicol 2009;56:623–30.
19. Castilhos ZC, Rodrigues-Filho S, Rodrigues AP, et al. Mercury contamination in fish from gold mining areas in Indonesia and human health risk assessment. Sci Total Environ 2006;368:320–5.
20. Riddell TJ, Solon O, Quimbo SA, Tan CM, Butrick E, Peabody JW. Elevated blood-lead levels among children living in the rural Philippines. Bull World Health Org 2007;85:674–80.
21. Lo YC, Dooyema CA, Neri A, et al. Childhood lead poisoning associated with gold ore processing: a village-level investigation-Zamfara State, Nigeria, October-November 2010. Environ Health Perspect 2012;120:1450–5.
22. Médecins Sans Frontières. Lead Poisoning Crisis in Zamfara State Northern Nigeria. Briefing paper. Geneva, Switzerland: Médecins Sans Frontières. Available at: http://www.msf.org/en/article/lead-poisoning-crisis-zamfara-state-northern-nigeria; 2012. Accessed December 9, 2015.
23. Dooyema CA, Neri A, Lo YC, et al. Outbreak of fatal childhood lead poisoning related to artisanal gold mining in northwestern Nigeria, 2010. Environ Health Perspect 2012;120:601–7.
24. US Environmental Protection Agency (EPA). Superfund Lead-Contaminated Residential Sites Handbook. Washington, DC: EPA. Available at: http://www.epa.gov/superfund/lead/products/handbook.pdf; 2003. Accessed December 10, 2015.
25. Guangwei H. China's Dirty Pollution Secret: The Boom Poisoned Soil and Crops. New Haven, CT: Yale Environment 360. Available at: http://e360.yale.edu/feature/chinas_dirty_pollution_secret_the_boom_poisoned_its_soil_and_crops/2782; 2014. Accessed December 21, 2015.
26. Caravanos J, Gualtero S, Dowling R, et al. A simplified risk-ranking system for prioritizing toxic pollution sites in low-and middle-income countries. Ann Global Health 2014;80:278–85.
27. World Bank. 2015 Country Data Sheets. Washington, DC: World Bank. Available at: http://data.worldbank.org/country/Ghana; 2015. Accessed December 9, 2015.
28. Oteng-Ababio M, Forkuo Amankwaa E, Chama MA. The local contours of scavenging for e-waste and higher-valued constituent parts in Accra, Ghana. Habitat Int 2014;43:163–71.
29. Wilson ML, Renne E, Roncoli C, et al. Integrated assessment of artisanal and small-scale gold mining in Ghana—part 3: social sciences and economics. Int J Environ Res Public Health 2015;12:8133–56.
30. Bennett S, Woods T, Liyanage WM, Smith DL. A simplified general method for cluster-sample surveys of health in developing countries. World Health Stat Q 1991;44:98–106.
31. Ghana Statistical Service; 2015. Available at: http://www.statsghana.gov.gh. Accessed December 10, 2015.
32. Ghana Chamber of Mines; 2013. Available at: http://ghanachamberofmines.org/media/publications/Performance_of_the_Mining_Industry_in_2013.pdf. Accessed December 8, 2015.
33. Human Rights Watch. Precious Metal, Cheap Labor. New York, NY: Human Rights Watch. Available at: https://www.hrw.org/report/2015/06/10/precious-metal-cheap-labor/child-labor-and-corporate-responsibility-ghanas; 2015. Accessed December 10, 2015.