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Article

Health and Economic Consequences of Lead Exposure Associated with Products and Services Provided by the Informal Economy

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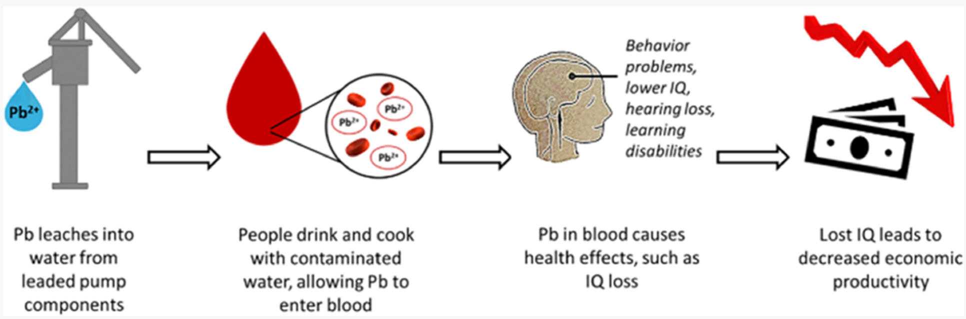

ABSTRACT: In low- and middle-income countries (LMICs), the presence of an informal economy can lead to human exposure to toxic metals such as lead (Pb). This paper demonstrates the local health and economic benefits of modifying practices within the informal economic sector in Madagascar. Specifically, leaded components in 504 locally manufactured household water pumps were replaced with unleaded components. Prior to the intervention, 32% of the household systems exhibited lead concentrations above the World Health Organization (WHO) provisional drinking water guideline of 10 μg/L, but after the intervention, fewer than 3% of the systems were in exceedance. The reduction of lead concentration is modeled to reduce the fraction of children with elevated BLLs (>5 μg/dL) from 34 to 13%. The reduction in BLLs is estimated to provide an average economic benefit of US$11 800 per child based on predicted increases in lifetime productivity. This corresponds to a total benefit of US$8.7 million for the 730 children aged 1−5 associated with the pumps, representing a return on investment of greater than 1000-to-1. Results demonstrate how the formation of partnerships between public, private, and civil society entities, as suggested by UN Sustainable Development Goal 17, can realize important local economic and health benefits in LMICs.

KEYWORDS: *Africa, environmental exposure, chemical pollution, recycling, blood lead, IQ, health, Sustainable Development Goals, IEUBK*

■ INTRODUCTION

Pollution disproportionately affects the health and well-being of those living in low- and middle-income countries (LMICs).[1] One chemical pollutant that poses multiple health risks is lead (Pb), which now accounts for 1.06 million annual premature deaths and 24.4 million disability-adjusted life years (DALYs) worldwide.[2] Lead exposure also accounts for large percentages of idiopathic developmental intellectual disability (IQ loss), hypertensive heart disease, ischemic heart disease, and stroke.[3] For children, the World Health Organization (WHO) states that lead is associated with neurobehavioral damage at blood lead levels (BLLs) as low as 5 μg/dL, and that any lead exposure is associated with harm to the developing fetus.[4] Unfortunately, a recent study reports approximately 800 million children globally (1 in 3 children) are at or above that 5 μg/dL BLL standard.[3,5] In addition, children with nutritional deficiencies experience increased absorption of lead.[6] Worldwide, there are estimated to be 149 million such children under 5 years old, with ≥75% of the cases in LMICs.[7]

Lead has, however, been used for centuries for a variety of reasons. It has favorable material properties for use in manufacturing that include electrical conductivity, low melting point, workability, and a vibrant color. Accordingly, it has found its way into numerous occupational workplaces and household products.[8] Hence, although lead can be found naturally in the environment, most lead exposure is associated with anthropogenic activities related to extraction and use of the metal.[9,10] In LMICs, adverse lead exposure has been

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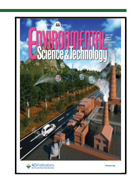

identified with informal battery recycling[3] and mining.[11−13] In addition, the presence of lead in locally sourced and manufactured pottery, seafood, fruits and vegetables, spices, and medicinal supplements likely contributes to high BLLs.[14−18] Other identified uses of lead include subsistence fishing via the manufacturing of fishing sinkers,[19] cooking vessels,[20] and household water pumps.[21] The continued use of lead in such a wide variety of products and industries is one of the reasons that millions of children worldwide continue to suffer from elevated BLLs.[3]

Lead products in commerce can, in principle, be regulated to protect public health; for example, leaded gasoline is reported to now be sold in just one country in Africa, Algeria.[3,22] However, a daunting challenge is eliminating lead exposure associated with products manufactured, sold, and serviced by the informal sector in LMICs. The term informal sector commonly refers to small businesses and/or individuals (e.g., street vendors and artisans) who produce ordinary goods and services and operate at the fringes of the formal economy.[23−25] In much of the world, this informal sector dominates the economy. For instance, in Sub-Saharan Africa, these small businesses can account for at least 80% of total nonagricultural employment, up to 60% of a country's gross domestic product (GDP), and as much as 93% of new employment.[24] Similar large percentages of informal-sector employment are recorded in Asia (65%) and Latin America (51%).[26]

The combination of lead's useful properties and the importance of the informal economic sector have led to routes of increased lead exposure. For example, reverse supply chains, such as battery recycling that occur in informal market sectors of LMICs, have been examined with regard to environmental and health impacts of open burning of materials and the lack of regulations.[27] Informal battery recycling is also an important route of lead exposure.[3] As just one example, in the suburbs of Dakar (Senegal), it was reported that child BLLs ranged from 39.8 to 613.9 μg/dL with 82% of the sample having life-threatening BLLs greater than 70 μg/dL resulting from informal recycling of used lead-acid batteries.[28]

Another example of an informal market that uses leaded components, which will be used as a case study in this paper, is in the coastal city of Toamasina, Madagascar. Toamasina has experienced rapid urbanization over the past decades, especially in the expansion of informal urban/peri-urban settlements. Within the context of our study location, urban/peri-urban refers to an area within an administrative boundary where a significant majority of the population is not primarily engaged in agriculture.[29] The municipal water provider is challenged by operational inefficiencies and lacks the capacity to upgrade aging infrastructure; thus, thousands of households either cannot afford or do not have access or continual service to piped utility water. In response, a demand has emerged for manually driven well points affixed with a locally produced hand pump (referred to as Pompe Tany). The Pompe Tany is a type of manually operated suction pump that traditionally has been manufactured with lead components by local artisans and technicians in small workshops. It is estimated that 9000 of these water supply systems exist in Toamasina that serve 170 000 individuals.[21] Anthropogenic lead concentrations in the water from these systems were shown to frequently exceed the WHO guideline of 10 μg/L,[30] and elevated BLLs are estimated to occur in some children from exposure to drinking water and eating rice and other starches cooked in the pump water.[31] Consistent with these observations, a recent study estimated that Madagascar lost US$117−166 million in 2015 due to lost productivity from pollution, with lead pollution identified as one of the primary causes.[32]

In some respects, these informal activities represent sound waste management by prioritizing reuse of waste products over simple disposal, a key concept in the pollution prevention hierarchy.[33] In fact, approximately 50% of lead originates from recycled materials.[34] However, it is essential to recognize the unintended health and economic consequences of this strategy. For example, the WHO (2015) reports that IQ loss from lead exposure results in US$134.7 billion lost to the African economy each year.[8] Thus, while supportive of the ingenuity of actors in the informal sector, we posit that there exists a vital need to partner with the informal sector through education, training, and external support, so this significant sector of the global economy can provide improved products that bring about health, economic, and environmental benefits. One strategy to provide such improved products is through the application of principles of green engineering. In particular, we endorse the principle that all material and energy inputs and outputs of products endeavor to be as innately nonhazardous as possible.[35]

Therefore, the overall objective of this paper is to demonstrate the local health and economic benefits that can be generated when an informal-sector industry modifies its practices to employ safer approaches (i.e., alternative materials). We use the Pompe Tany industry in Toamasina, Madagascar, as a case study that exemplifies broadly applicable principles. To achieve the overall objective, this study had the following specific goals: (1) measure concentrations of lead in pumped water before and after replacing leaded pump components in over 500 pumps; (2) estimate BLLs of children in households that use Pompe Tany with and without leaded components; (3) quantitatively estimate IQ loss and DALYs associated with lead exposure in Toamasina; and (4) estimate economic loss associated with lead exposure and economic benefits of the intervention (i.e., the retrofitting of pumps with unleaded components). Through these goals, our study provides a complete picture of the potential localized health and economic impacts of informal sectors.

This study is driven by multiple Sustainable Development Goals (SDGs) including goal 3 (good health and well-being), goal 6 (clean water and sanitation), goal 8 (decent work and economic growth), goal 12 (responsible consumption and production), and goal 17 (partnerships (that includes capacity building)).[36] Furthermore, our study provides a more complete picture of the impact that informal-sector practices can have on local health and economies or residents. This contrasts with previous studies focused on estimating country-wide and continental impacts of lead exposure in LMICs.[8,37] Importantly, the principles demonstrated in this paper can easily be replicated in other parts of the world to support the informal sector while also improving health and economic well-being.

■ MATERIALS AND METHODS

Project Site and Description of Intervention. Toamasina is a city in eastern coastal Madagascar where many households access shallow groundwater using a manually driven well connected to a manually operated suction pump.[21] The pumps are manufactured locally by artisans and technicians, who historically have used recycled lead for weights to operate check valves (i.e., piston and foot valves) in

Table 1. Modeling Blood Lead Levels in Children; Categorized Pump Data; and Integrated Exposure Uptake Biokinetic (IEUBK) Model Inputs

	Pb range (μg/L)	# of pumps	IEUBK inputs: median flushed Pb concentration[a] (μg/L)	dietary uptake[b] (μg/day): 1−2 yo[c]	2−3 yo[c]	3−4 yo[c]	4−5 yo[c]
preintervention	0−2	43[d]	2	1.17	1.44	1.58	1.71
	3−5	66	4	2.34	2.88	3.16	3.43
	6−10	55	8	4.69	5.77	6.33	6.86
	11−20	42	14	8.20	10.10	11.07	12.00
	21−100	38	28	16.41	20.19	22.15	24.00
postintervention	0−2	330[e]	2	1.17	1.44	1.58	1.71
	3−5	68	3	1.76	2.16	2.37	2.57
	6−10	10	7.5	4.39	5.41	5.93	6.43
	11−20	4	12.5	7.32	9.01	9.89	10.72
	21−100	6	44	25.78	31.73	34.80	37.72

[a]For the 0−2 category, we used 2 μg/L for modeling purposes; for all other categories, we used the median "measured" concentration within that category. [b]Dietary uptake for each category was estimated using the procedures of Akers et al. (2020). [c]yo: Years old. [d]In the preintervention measurements, the measured Pb concentration was 2 μg/L for 20 wells and was below the detection limit of 2 μg/L for 23 wells. [e]In the postintervention measurements, the measured Pb concentration was 2 μg/L for 64 wells and was below the detection limit of 2 μg/L for 266 wells.

the pumps. Water delivered by the pumps is used for both nonpotable and potable uses, including drinking and cooking.[31] In an initial study of 18 households using these pumps, it was observed that lead is detectable in the pumped water, frequently at concentrations above 10 μg/L, and occasionally at levels exceeding 40 μg/L.[30] It was estimated that the presence of this lead in the water correlates with elevated BLLs in children.[30,31]

In 2018, we worked with local pump technicians to replace the lead weights in both check valves with iron (Fe) weights in 504 of these household pump systems. During this retrofit of the piston and foot valve, no plumbing (i.e., piping) below the pump is disturbed, and the only item removed is the pump head (Figure S2). Pumps throughout the study area were selected based on (1) the ability to oversee adaptations and (2) household willingness to participate in the project. Based on surveys completed by the owners of the pumps at the time of the retrofit, we estimate that 730 children between the ages of 1 and 5 years old were served by the 504 pumps.

Measurement of Lead (Pb) Concentrations in Pumped Water. Standard sampling for lead contamination in plumbing water requires an extended period of stagnation and collection of a "first-draw" water sample for lead concentration analysis.[38] The sample collection is typically conducted by the household resident, allowing for this initial sample collection prior to household water use. However, for a communal water source, this was not feasible. These water systems are typically the only water source for several households, and it was not practical to restrict access prior to sampling. Instead, the protocol for collecting water was adjusted to consistently sample fully flushed water samples. This approach has been used by a variety of previous studies that require sampling public sources.[39,40] In the present study, a volume of 15 L (approximately one to five well volumes) was purged from the system and discarded. This was performed to ensure that all water collected subsequently represented a "flushed" sample of water. Following the 15 L purge, another 15 L were pumped into a bucket from which a 10 mL glass pipette was rinsed, and a 5 mL aliquot was immediately collected and analyzed on-site for the concentration of lead.

Analysis of lead in the water was performed with a Palintest Scanning Analyzer SA1100 (Erlanger, KY). This method uses anodic stripping voltammetry and follows EPA Method 101.[41,42] This analysis does not account for particulate lead and no acidification was performed on samples. The Palintest SA1100 reports aqueous lead concentrations in the range 2−100 μg/L. ICP instrumentation was not available to quantify lower detection limits. Concentrations below 2 μg/L are reported by the SA100 as "lower than limit of detection" and concentrations above 100 μg/L are reported as "higher than test range." Water samples were collected from a subset of the 504 rehabilitated pump systems before and after the check-valve replacement; specifically, 244 pumps prior to the intervention and 418 pumps following the intervention. Two hundred and twenty-five of the rehabilitated pumps had paired sample data, i.e., Pb concentrations were measured both before and after the retrofit in 225 of the wells.

Estimation of Blood Lead Levels (BLLs). We used Windows version 11, Build 1.1, of the Integrated Exposure Uptake Biokinetic (IEUBK) Model, developed by the U.S. Environmental Protection Agency,[43] to estimate BLLs in children aged 1−5 years. This model is able to predict distributions of BLLs in children based on known or assumed exposure to lead.

To perform the modeling, we subdivided the population of children into four age groups: 1−2, 2−3, 3−4, and 4−5 years. For simplicity, we assumed that the overall population of children was split evenly among these four age groups. This assumption was chosen as no breakdown of a Malagasy population to the 1 year level is available, and there is no known reason to expect any significant differences between the number of children in these age groups. These age groups were further divided into five subgroups, corresponding to different concentrations of lead in the household water. The five concentration subgroups were 0−2 μg/L (2 μg/L: the lower detection limit of testing equipment), 3−5, 6−10 μg/L (10 μg/L: the WHO drinking water guideline), 11−20, and >20 μg/L. These groupings allowed for a relatively uniform spread between groups with no group containing more than 30% of the wells tested prior to retrofitting. To decide the fraction of children in each of these five concentration categories, we used the measured concentrations of lead in the household pump systems, distinguishing between the preintervention lead measurements and the postintervention lead measurements.

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For instance, in the 244 pumps measured prior to check-valve replacement, 22.5% of the wells exhibited a lead concentration between 6 and 10 μg/L, so we assumed that 22.5% of "preintervention" children belonged to this category. However, in the 418 pumps measured after the check-valve replacement, only 2.4% of the wells exhibited a concentration between 6 and 10 μg/L, so we assumed that 2.4% of "postintervention" children belonged to this category. Thus, overall, we considered 20 groups of children for the preintervention IEUBK modeling (four age groups, five concentration groups) and 20 groups of children for the postintervention IEUBK modeling. After completing the IEUBK modeling for each subgroup individually, the results were recombined, weighted according to the fraction of children in each subgroup. This produced a predicted distribution of BLLs for children using nonretrofitted (preintervention) wells and a separate predicted distribution of BLLs for children using retrofitted (postintervention) wells.

Within each modeling group, the IEUBK requires certain input data for exposure routes related to drinking water, diet, air, soil, and dust.[44] We used default model values for air and for soil and dust as no local lead measurements for air or soil and dust are known for this region. For drinking water, we used the median measured lead concentration for each of the five concentration subgroups; for instance, within the 6−10 μg/L subgroup, the median measured concentration was 8 μg/L in the preintervention wells and 7.5 μg/L in the postintervention wells. Because the Palintest instrument has a lower measurement limit of 2 μg/L, we do not know the median water concentration in the 0−2 μg/L subgroups, and we therefore assumed a concentration of 2 μg/L for these groups to be conservative. For diet, we used the methods described by Akers et al.[31] which adjusted the inputs to fit a Malagasy diet. Model inputs are summarized in Table 1.

Estimation of IQ Loss and DALYs. It is well known that exposure to lead can result in intellectual disability including loss of IQ.[45−47] Furthermore, childhood exposure to lead can result in a decline of cognitive function and socioeconomic status in adulthood.[48] Therefore, to quantify the health impact of lead exposure to children in Toamasina, we estimated the IQ loss and the resultant disability-adjusted life years (DALYs).

Different research groups have proposed different quantitative relationships between BLL and IQ loss, but most studies agree that a 10 μg/dL increase in BLL results in a loss of about 1−4 IQ points.[45,46] Here, we used the following equation, which is based on the results of Lanphear et al.[49] and applies to children with BLL greater than 2.4 μg/dL.[49] The paper of Lanphear et al.[49] is a pooled analysis of seven studies: four from the United States, one from Australia, one from Mexico, and one from the former Yugoslavia. The findings of Lanphear et al.[49] are widely cited and have been used in multiple studies examining LMICs.[50,51]

$$\text{IQ loss} = 6.2903 \log_{10}(\text{BLL}) - 2.3886 \quad (1)$$

Using this equation, the estimated distributions of BLLs were used to estimate distributions of lost IQ points. This was done by subtracting the modeled IQ loss distribution from a "baseline" IQ distribution (mean of 100 and standard deviation of 15) to represent the estimated change seen in the local Malagasy child population. Thus, three different IQ distributions can be compared: a baseline IQ distribution for a population not exposed to lead, the IQ distribution of Toamasina children using water from nonretrofitted (preintervention) pumps, and the IQ distribution of Toamasina children using water from rehabilitated (postintervention) pumps.

The IQ loss caused by lead exposure can then be used to estimate DALYs for children in Toamasina. A disability-adjusted life year (DALY) is based on years of life lost (YLL) and years lost due to disability (YLD). Because mild intellectual disability should not result in death, YLL was assumed to be zero, and thus DALY was assumed to be equivalent to YLD. YLD is estimated as the number of prevalent cases times a disability weight. There are five possible disability weights for lead-related intellectual disability, varying with the severity of the disability, as shown in Table 2. The five categories represent borderline, mild, moderate, severe, and profound intellectual disability.

Table 2. Disability Weights (DW) for Severity Levels of Intellectual Disability

		disability weight	
IQ range	severity of intellectual disability	GBD 2016[ac]	GHE 2016[bc]
70−85	borderline	0.011	0.011
50−69	mild	0.043	0.127
35−49	moderate	0.100	0.293
20−34	severe	0.160	0.383
<20	profound	0.200	0.444

[a]GBD 2016: Global Burden of Disease 2016 assessment. [b]GHE 2016: Global Health Estimates. [c]WHO (2018).[52]

For each of these five categories, the number of prevalent cases (per 1000 children) is determined simply from the estimated IQ distributions (previously described). Also, for each category, two different disability weights have been estimated, the global burden of disease estimates (GBD) and the more comprehensive WHO-endorsed global health estimates (GHE), as shown in Table 2.[52] Here, we estimated DALYs using both sets of disability weights, thereby estimating a range of DALYs. Also, the disability weights shown in Table 2 are multiplied by an adjustment factor of 2.05, which accounts for increased consequences of mental impairment in African regions with high child and adult mortality, a category in which Madagascar is included.[9] The adjustment factor was calculated by the WHO and uses the assumption that noncongenital causes of intellectual impairment (i.e., anemia, hookworm infection, etc.) are discrete and additive, but does not adjust for factors of malnutrition.[9] The overall calculation of DALYs is performed by multiplying the number of prevalent cases times the (adjusted) disability weight for each of the five categories, then summing to calculate the overall result. This yields an estimate of DALYs per 1000 children.

Estimation of Economic Impact. It is known that intellectual impairment from environmental neurotoxins and neurotoxicants contribute to lost economic productivity, and that the economic cost of this lost productivity increases with the severity of the intellectual impairment.[22,51,53,54] These costs are sometimes referred to as lost opportunity costs and do not consider other societal costs such as increases in crime rates or the need for special education services. The attributable cost due to lead exposure from pump water was calculated following the method presented by Attina and Trasande.[51]

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$$\text{cost} = \sum_{i=1}^{N} \text{EAF}_i(\text{IQ loss})_i \left(\frac{\text{lost economic productivity}}{\text{IQ loss}}\right) \quad (2)$$

In this equation, the following definitions and estimations apply.

- N is the number of children aged 1−5 associated with the 504 pumps rehabilitated during the intervention. Because each child obtains some benefits from the decreased exposure to lead, N = 730.
- EAF_i indicates the environmentally attributable fraction of lead for the i^{th} child. For this study, EAF_i was assumed to be 1.0 for all children, based on an assumption that little lead exposure is due to natural processes.[51]
- $(\text{IQ loss})_i$ indicates the lead-related IQ loss for the i^{th} child. Although we do not know the BLL or the IQ loss for any individual child, we estimated the distribution of IQ loss, as described above. By randomly sampling this distribution N times, we are able to obtain the required N individual estimates of $(\text{IQ loss})_i$.
- A lost economic productivity of US$16 500 per lost IQ point was used here, based on estimates of Attina and Trasande (2013) for lost economic productivity in Eastern Africa which included Madagascar.[51] The value of US$16 500 per IQ point recommended by Attina and Trasande[51] is consistent with other estimates, which have ranged from ∼US$12 000 to 26 000 per lost IQ point.[55,56]

Equation 2 was applied to both the preintervention and postintervention distributions of children, i.e., to children using nonrehabilitated wells and to children using rehabilitated wells. The difference between the costs of these two distributions represents the cost saved by performing the intervention.

The total cost of the intervention was also calculated. The rehabilitation of an individual pump costs approximately US$4 per pump for locally sourced materials and labor to replace the components of the pump's foot valve and piston valve.

RESULTS AND DISCUSSION

Measurement of Lead (Pb) Concentrations in Pumped Water. The concentrations of lead measured in the pumped water pre- and postintervention are presented in Figure 1. Prior to the intervention, 33% of measured lead concentrations (n = 244) exceeded the WHO (2014) provisional guideline of 10 μg/L, and some of the measured concentrations even exceeded 100 μg/L. After retrofitting the pumps with nonleaded components, the measured lead concentrations (n = 418) were below 10 μg/L in 98% of samples.

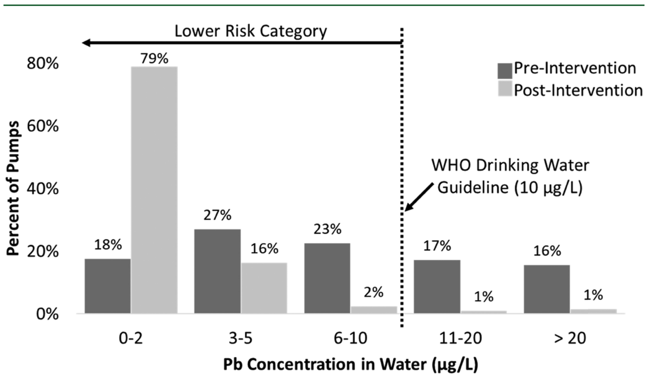

Figure 1. Distributions of measured lead concentrations in pumped household water before and after pump retrofit with unleaded components. Dark gray: Preintervention concentrations (n = 244). Light gray: Postintervention concentrations (n = 418).

A Wilcoxon signed-rank test of the paired data showed that the retrofit of the pump significantly reduced the lead concentration in the pumped water (Z = −11, p < .001). More information about this analysis and the paired pre- and postintervention data can be found in the Supporting Information.

Underestimation of lead concentration in water is likely, representing lower bounds, due to flushing of the system before sampling. For wells that are used frequently throughout the day, flushed conditions are expected to prevail, and the measured Pb concentrations are likely representative of actual conditions; for wells that are used only sporadically, the concentrations reported here may underestimate the stagnant or first-draw conditions (cf. Akers et al.[30]).

Leaded solder has been phased out in many parts of the world,[57] but it is still used in Madagascar. The varying levels of lead seen in the pumped water postintervention are potentially attributable to the age of the well-screen solder, as lead release from solder is reported to decrease over time.[57] Examination of the well screen and leaching of lead from solder was beyond the scope of this paper but is an important aspect to be examined with future studies and efforts to engage with agents in the informal economic sectors, such as pump technicians.

Estimation of Blood Lead Levels (BLLs). The estimated distributions of BLLs for children in Toamasina (aged 1−5), accounting for modified water and dietary lead uptake and holding other variables constant (i.e., air, soil, and dust lead uptake values), are provided in Figure 2. Figure 2 presents estimated BLL distributions for children using water (associated with drinking and cooking) from nonretrofitted (preintervention) pumps and from retrofitted (postintervention) pumps. The figure shows that approximately 34% of children using nonretrofitted pumps are estimated to have BLLs over 5 μg/dL. However, for children using retrofitted pumps, only 13% would have a BLL above 5 μg/dL.

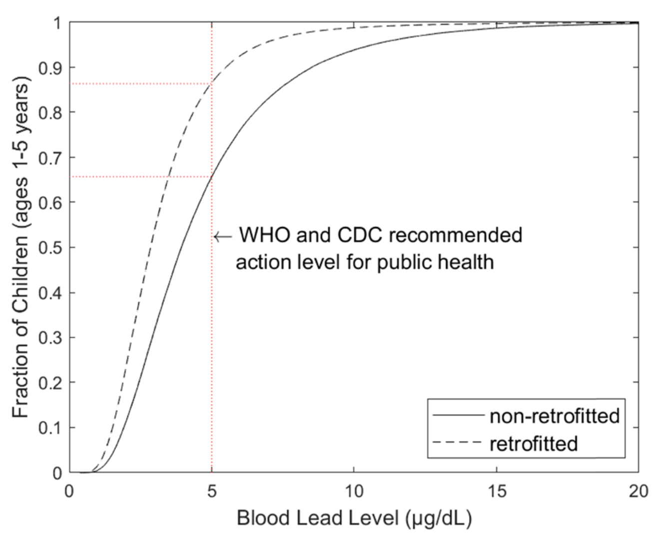

Figure 2. Estimated cumulative distributions of blood lead levels (BLLs) in children using water from nonretrofitted pumps and from retrofitted pumps.

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The reference level of 5 μg/dL is a widely accepted threshold established by the US Centers for Disease Control and Prevention (CDC) and is recognized by the WHO to be associated with irreversible health impacts.[2,4,58] However, several studies have shown health risks linked to levels below 5 μg/dL,[59,60] indicating that children with any BLL could experience some negative impact. The shift in the estimated BLL distributions (Figure 2) therefore indicates that the removal of lead components from the pumps not only lowers the concentration of lead in the pumped water but may also improve the health of those using the pumps. However, BLLs are not expected to decrease immediately upon the removal of leaded components from the pump, because the half-life of lead in blood is 1−2 months.[61]

Estimation of IQ Loss and DALYs. Estimated BLL distributions were used to estimate distributions of IQ in children in Toamasina. Figure 3 shows three estimated IQ distributions. One is a baseline IQ distribution with a mean of 100 and a standard deviation of 15, which corresponds to a population of children with no significant lead exposure. The other two IQ distributions shown in this figure correspond to children using nonretrofitted wells (preintervention) and children using retrofitted wells (postintervention); that is, the IQ distributions in Figure 3 correspond to the BLL distributions in Figure 2. Figure 3 shows that if leaded components are not removed from the pumps, exposure to lead in household water is estimated to decrease the IQ distribution of children in Toamasina by about two points on average. That decrement is lowered to about one IQ point as a result of the intervention (Figure 3).

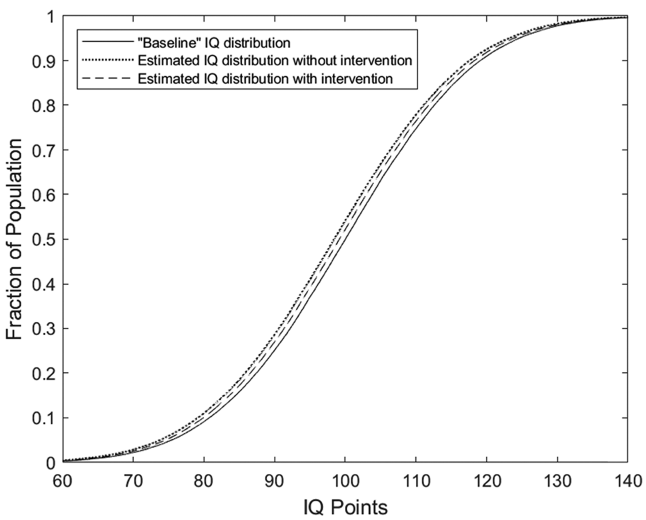

Figure 3. Estimated IQ distributions without a pump intervention and with a pump intervention compared to a baseline IQ distribution with a mean of 100 and a standard deviation of 15.

The results from the DALY calculations indicate 1.0−2.2 DALYs per 1000 children if no intervention were to take place, and only 0.5−1.1 DALYs per 1000 children once pumps were retrofitted (postintervention). These DALY estimates are low because they only account for IQ decrements and do not account for other health impacts that lead is known to cause.[62]

Based on the ranges of DALYs given above, we estimate that the intervention we performed may save 0.4−1.0 DALYs for the 730 children using the 504 retrofitted pumps. If this number is extrapolated to consider all 9000 pumps that are estimated to be present in Toamasina,[21] it suggests that removing lead from household pumps may save 8.0−20.0 DALYs for children in Toamasina, based solely on the prevention of IQ loss.

Estimates of ∼21.7 million DALYs due to lead exposure globally have been reported with ∼1.5 million DALYs in Sub-Saharan Africa.[63] Within Madagascar, these estimates suggest ∼1000 DALYs attributable to lead exposure. These estimates include death attributable to lead exposure as well as adult DALYs (including other health concerns such as cardiovascular diseases) which our study did not consider.

Estimation of Economic Impact. For the 730 children aged 1−5 using the pumps treated in this study, the lost economic productivity preintervention was estimated to be US $18.7 million over the children's lifetimes. Following the intervention (retrofitting of pumps), the lost economic productivity due to the continued presence of some lead in the environment was reduced to US$10.0 million. Therefore, the intervention performed here is estimated to have saved US $8.7 million in recovered productivity over the lifetime of the 730 children. This is equivalent to US$11 800 per child. For context, this is over 7 times Madagascar's 2019 GDP per capita of $1647.[64] As previously mentioned, this calculation is based only on IQ loss and does not consider other societal costs and benefits such as crime rates or special education services.

The total cost of the intervention if households would individually contract a pump technician includes the cost for locally sourced labor and materials for the 504 pump adaptations (∼US$2000 total). This equates to ∼US$2.76 per child. However, the estimated cost of US$2.76 per child accounts only for the 730 children aged 1−5 that are associated with the pumps, and it does not account for adults or older children that might also benefit from the retrofit. If all beneficiaries of the retrofit are considered, the per-person cost would be even lower.

These results indicate that for every dollar spent on this intervention, ∼US$4000 is saved in economic productivity. This return on investment is higher than what has been observed in most lead mitigation studies. For example, a return of US$17−221 for each dollar invested in lead hazard control in the United States has been reported by Gould (2009), also noted by WHO (2010).[4,56] Other water and sanitation improvements (i.e., chlorination, piped water, and provision of improved sanitation) in LMICs were estimated to have returns of US$5−46.[65]

Economic losses due to lead exposure have also been estimated on a continental scale; for example, Attina and Trasande[51] estimate 98.2 million IQ points lost or US$134.7 billion in economic losses in Africa due to lead exposure.[51] On a global scale, the estimation of losses of lifetime earnings in LMICs attributable to lead exposure range from US$729.6 to 1162 billion annually.[3] These large-scale estimates point toward the need to address lead exposure in LMICs. In this study, the estimated US$8.7 million saved and a return on investment of ∼US$4000 for every dollar spent on the intervention demonstrates the importance of not only further identifying sources of exposure to lead and other chemical pollutants, but also potential mitigation strategies that engage with local agents in the informal economic sectors. Social/behavioral approaches can also be used to address needs, concerns, and current behaviors of these local agents to support them in innovating improved products that maintain their function but also result in improved well-being.[66] The

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results presented in this study also demonstrate how the formation of partnerships between public, private, and civil society entities, as suggested by UN Sustainable Development Goal 17,[36] can realize important local economic and health benefits.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.0c08127.

Study location; pitcher pump schematic and remediation process; paired pre- and postremediation data; and navigating and supporting collaborations in interactions with local partners (PDF)

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Author Contributions

The manuscript was written through contributions of all authors and all authors have contributed to the study. L.J.P.B. and M.U. oversaw field measurements of water quality with inputs in the study design from other authors. A.M.B. and J.A.C. led the modeling efforts of health and economic impacts with inputs and reviews performed by other authors. All authors have given approval to the final version of the manuscript.

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Notes

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■ ABBREVIATIONS

Pb	lead
LMIC	low- and middle-income countries
WHO	World Health Organization
EPA	Environmental Protection Agency
Fe	iron
SDG	Sustainable Development Goal
DALY	disability-adjusted life year
YLD	years lost due to disability
YLL	years of life lost
DW	disability weight
IQ	intelligence quotient

■ REFERENCES

(1) Landrigan, P. J.; Fuller, R.; Acosta, N. J. R.; Adeyi, O.; Arnold, R.; Basu, N. N.; Baldé, A. B.; Bertollini, R.; Bose-O'Reilly, S.; Boufford, J. I.; Breysse, P. N.; Chiles, T.; Mahidol, C.; Coll-Seck, A. M.; Cropper, M. L.; Fobil, J.; Fuster, V.; Greenstone, M.; Haines, A.; Hanrahan, D.; Hunter, D.; Khare, M.; Krupnick, A.; Lanphear, B.; Lohani, B.; Martin, K.; Mathiasen, K. V.; McTeer, M. A.; Murray, C. J. L.; Ndahimananjara, J. D.; Perera, F.; Potočnik, J.; Preker, A. S.; Ramesh, J.; Rockström, J.; Salinas, C.; Samson, L. D.; Sandilya, K.; Sly, P. D.; Smith, K. R.; Steiner, A.; Stewart, R. B.; Suk, W. A.; Van Schayck, O. C. P.; Yadama, G. N.; Yumkella, K.; Zhong, M. The Lancet Commission on Pollution and Health. *Lancet* **2018**, *391*, 462−512.

(2) World Health Organization, *Lead Poisoning and Health*. https://www.who.int/news-room/fact-sheets/detail/lead-poisoning-and-health.s

(3) Rees, N.; Fuller, R. *The Toxic Truth: Children' s Exposure to Lead Pollution Undermines a Generation of Future Potential*; UNICEF, 2020.

(4) World Health Organization, *Childhood Lead Poisoning*, Geneva, Switzerland, 2010.

(5) Ericson, B.; Hu, H.; Nash, E.; Ferraro, G.; Sinitsky, J.; Taylor, M. P. Blood Lead Levels in Low-Income and Middle-Income Countries: A Systematic Review. *Lancet Planet. Health* **2021**, *5*, e145−e153.

(6) Mahaffey, K. R. Nutrition and Lead: Strategies for Public Health. *Environ. Health Perspect.* **1995**, *103*, 191−196.

(7) Jensen, L. *The Sustainable Development Goals Report 2019*, United Nations, 2019.

(8) World Health Organization, *Lead Exposure in African Children Contemporary Sources and Concerns*, 2015.

(9) Fewtrell, L.; Kaufmann, R.; Prüss-Üstün, A. *Lead Assessing the Environmental Burden of Disease at National and Local Levels*, Prüss-Üstün, A.; Campbell-Lendrum, D.; Corvalán, C.; Woodward, A., Eds.; World Health Organization: Geneva, 2003.

(10) Kamenov, G. D.; Gulson, B. L. The Pb Isotopic Record of Historical to Modern Human Lead Exposure. *Sci. Total Environ.* **2014**, *490*, 861−870.

(11) Von Schirnding, Y.; Mathee, A.; Kibel, M.; Robertson, P.; Strauss, N.; Blignaut, R. A Study of Pediatric Blood Lead Levels in a Lead Mining Area in South Africa. *Environ. Res.* **2003**, *93*, 259−263.

(12) Yabe, J.; Nakayama, S. M. M.; Ikenaka, Y.; Yohannes, Y. B.; Bortey-Sam, N.; Oroszlany, B.; Muzandu, K.; Choongo, K.; Kabalo, A. N.; Ntapisha, J.; Mweene, A.; Umemura, T.; Ishizuka, M. Lead Poisoning in Children from Townships in the Vicinity of a Lead-Zinc Mine in Kabwe, Zambia. *Chemosphere* **2015**, *119*, 941−947.

(13) Bello, O.; Naidu, R.; Rahman, M. M.; Liu, Y.; Dong, Z. Lead Concentration in the Blood of the General Population Living near a Lead-Zinc Mine Site, Nigeria: Exposure Pathways. *Sci. Total Environ.* **2016**, *542*, 908−914.
(14) Cherfi, A.; Abdoun, S.; Gaci, O. Food Survey: Levels and Potential Health Risks of Chromium, Lead, Zinc and Copper Content in Fruits and Vegetables Consumed in Algeria. *Food Chem. Toxicol.* **2014**, *70*, 48−53.
(15) Forsyth, J. E.; Weaver, K. L.; Maher, K.; Saiful Islam, M.; Raqib, R.; Rahman, M.; Fendorf, S.; P. Luby, S. Sources of Blood Lead Exposure in Rural Bangladesh. *Environ. Sci. Technol.* **2019**, *53*, 11429−11436.
(16) Ismail, S.; Azhari, S.; Ngah, C. W. Z. C. W. Determination of Selected Toxic Metal (As, Cd, Pb) and Essential (Zn, Cu) Elements in Local Canned Seafood Products. *AIP Conf. Proc.* **2019**, *1972*, No. 030020.
(17) Okatch, H.; Ngwenya, B.; Raletamo, K. M.; Andrae-Marobela, K. Determination of Potentially Toxic Heavy Metals in Traditionally Used Medicinal Plants for HIV/AIDS Opportunistic Infections in Ngamiland District in Northern Botswana. *Anal. Chim. Acta* **2012**, *730*, 42−48.
(18) Clark, C. S.; Rampal, K. G.; Thuppil, V.; Roda, S. M.; Succop, P.; Menrath, W.; Chen, C. K.; Adebamowo, E. O.; Agbede, O. A.; Sridhar, M. K. C.; Adebamowo, C. A.; Zakaria, Y.; El-Safty, A.; Shinde, R. M.; Yu, J. Lead Levels in New Enamel Household Paints from Asia, Africa and South America. *Environ. Res.* **2009**, *109*, 930−936.
(19) Mathee, A.; Khan, T.; Naicker, N.; Kootbodien, T.; Naidoo, S.; Becker, P. Lead Exposure in Young School Children in South African Subsistence Fishing Communities. *Environ. Res.* **2013**, *126*, 179−183.
(20) Weidenhamer, J. D.; Kobunski, P. A.; Kuepouo, G.; Corbin, R. W.; Gottesfeld, P. Lead Exposure from Aluminum Cookware in Cameroon. *Sci. Total Environ.* **2014**, *496*, 339−347.
(21) MacCarthy, M. F.; Annis, J. E.; Mihelcic, J. R. Unsubsidised Self-Supply in Eastern Madagascar. *Water Altern.* **2013**, *6*, 424−438.
(22) United Nations Environment Programme, *Final Review of Scientific Information on Lead*, 2010.
(23) De Soto, H. *The Other Path: The Invisible Revolution in the Third World*; Harper and Row Publishers: New York, 1989.
(24) Benjamin, N. C.; Mbaye, A. A. The Informal Sector, Productivity, and Enforcement in West Africa: A Firm-Level Analysis. *Rev. Dev. Econ.* **2012**, *16*, 664−680.
(25) Perry, G. E.; Maloney, W. F.; Arias, O. S.; Fajnzylber, P.; Mason, A. D.; Saavedra-Chanduvi, J. The International Bank for Reconstruction and Development. In *Informality: Exit and Exclusion*; The World Bank: Washington, DC, 2007.
(26) *Decent Work and the Informal Economy*, Report of the Director-General, Report VI; International Labour Office: Geneva, 2002.
(27) Williams, E.; Kahhat, R.; Allenby, B.; Kavazanjian, E.; Kim, J.; Xu, M. Environmental, Social, and Economic Implications of Global Reuse and Recycling of Personal Computers. *Environ. Sci. Technol.* **2008**, *42*, 6446−6454.
(28) Haefliger, P.; Mathieu-Nolf, M.; Lociciro, S.; Ndiaye, C.; Coly, M.; Diouf, A.; Faye, A. L.; Sow, A.; Tempowski, J.; Pronczuk, J.; Filipe, A. P.; Bertollini, R.; Neira, M. Mass Lead Intoxication from Informal Used Lead-Acid Battery Recycling in Dakar, Senegal. *Environ. Health Perspect.* **2009**, *117*, 1535−1540.
(29) UNICEF, *State of World Children: Children in an Urban World*; United Nations Children's Fund (UNICEF): New York, NY, 2012.
(30) Akers, D. B.; Maccarthy, M. F.; Cunningham, J. A.; Annis, J.; Mihelcic, J. R. Lead (Pb) Contamination of Self-Supply Groundwater Systems in Coastal Madagascar and Predictions of Blood Lead Levels in Exposed Children. *Environ. Sci. Technol.* **2015**, *49*, 2685−2693.
(31) Akers, D. B.; Buerck, A.; MacC.arthy, M. F.; Cunningham, J. A.; Mihelcic, J. R. Estimates of Blood Lead Levels (BLLs) for Children in Coastal Madagascar: Accounting for Dietary Uptake of Lead (Pb). *Exposure Health* **2020**, *12*, 501−511.
(32) Global Alliance on Health and Pollution, *Madagascar Health and Pollution Action Plan Accelerating the Implementation of Actions to Reduce Pollution-Related Illness*, 2018.
(33) Pollution Prevention Hierarchy. In *Encyclopedia of Public Health*, Kirch, W., Ed.; Dordrecht Springer, 2008; p 1116.
(34) Holm, O.; Hansen, E.; Lassen, C.; Stuer-Lauridsen, F.; Kjolholt, J. *Heavy Metals in Waste*, Final Report; COWI Consulting Engineers and Planners: Denmark, 2002.
(35) Anastas, P. T.; Zimmerman, J. B. Design through the 12 Principles of Green Engineering. *Environ. Sci. Technol.* **2003**, *37*, 94A−101A.
(36) United Nations Department of Economic and Social Affairs, *The 17 Goals*. https://sdgs.un.org/goals.
(37) Ericson, B.; Caravanos, J.; Depratt, C.; Santos, C.; Cabral, M. G.; Fuller, R.; Taylor, M. P. Cost Effectiveness of Environmental Lead Risk Mitigation in Low- and Middle-Income Countries. *GeoHealth* **2018**, *2*, 87−101.
(38) U.S. Environmental Protection Agency, *Suggested Directions for Homeowner Tap Sample Collection Procedures*, Revised Version: May 2017, 2019.
(39) Akers, D. B. *Lead (Pb) Contamination of Water Drawn from Pitcher Pumps in Eastern Madagascar*; University of South Florida, 2014.
(40) Alfredo, K. A.; Lawler, D. F.; Katz, L. E. Fluoride Contamination in the Bongo District of Ghana, West Africa: Geogenic Contamination and Cultural Complexities. *Water Int.* **2014**, *39*, 486−503.
(41) Argent, V. A. *Method 1001: Lead in Drinking Water by Differential Pulse Anodic Stripping Voltammetry*; United States Environmental Protection Agency: Kentucky, 1999.
(42) Brezonik, P. L.; Brauner, P. A.; Stumm, W. Trace Metal Analysis by Anodic Stripping Voltammetry: Effect of Sorption by Natural and Model Organic Compounds. *Water Res.* **1976**, *10*, 605−612.
(43) United States Environmental Protection Agency, *Integrated Exposure Uptake Biokinetic Model for Lead in Children*; United States Environmental Protection Agency, 2010.
(44) The Technical Review Workgroup for Lead, *Guidance Manual For The Integrated Exposure Uptake Biokinetic Model For Lead In Children*, 1994.
(45) Schwartz, J. Low-Level Lead Exposure and Children's IQ: A Metaanalysis and Search for a Threshold. *Environ. Res.* **1994**, *65*, 42−55.
(46) Bellinger, D. C. Very Low Lead Exposures and Children's Neurodevelopment. *Curr. Opin. Pediatr.* **2008**, *20*, 172−177.
(47) Needleman, H. Lead Poisoning. *Annu. Rev. Med.* **2004**, *55*, 209−222.
(48) Reuben, A.; Caspi, A.; Belsky, D. W.; Broadbent, J.; Harrington, H.; Sugden, K.; Houts, R. M.; Ramrakha, S.; Poulton, R.; Moffitt, T. E. Association of Childhood Blood-Lead Levels with Cognitive Function and Socioeconomic Status at Age 38 Years and with IQ Change and Socioeconomic Mobility between Childhood and Adulthood. *JAMA* **2017**, *317*, 1244−1251.
(49) Lanphear, B. P.; Hornung, R.; Khoury, J.; Yolton, K.; Baghurst, P.; Bellinger, D. C.; Canfield, R. L.; Dietrich, K. N.; Bornschein, R.; Greene, T.; Rothenberg, S. J.; Needleman, H. L.; Schnaas, L.; Wasserman, G.; Graziano, J.; Roberts, R. Low-Level Environmental Lead Exposure and Children's Intellectual Function: An International Pooled Analysis. *Environ. Health Perspect.* **2005**, *113*, 894−899.
(50) Ericson, B.; Dowling, R.; Dey, S.; Caravanos, J.; Mishra, N.; Fisher, S.; Ramirez, M.; Sharma, P.; McCartor, A.; Guin, P.; Taylor, M. P.; Fuller, R. A Meta-Analysis of Blood Lead Levels in India and the Attributable Burden of Disease. *Environ. Int.* **2018**, *121*, 461−470.
(51) Attina, T. M.; Trasande, L. Economic Costs of Childhood Lead Exposure in Low- and Middle-Income Countries. *Environ. Health Perspect.* **2013**, *121*, 1097−1102.
(52) Department of Information Evidence and Research, In *WHO Methods and Data Sources for Global Burden of Disease Estimates 2000−2016*, 2018.

(53) Bierkens, J.; Buekers, J.; Van Holderbeke, M.; Torfs, R. Health Impact Assessment and Monetary Valuation of IQ Loss in Pre-School Children Due to Lead Exposure through Locally Produced Food. *Sci. Total Environ.* **2012**, *414*, 90−97.
(54) Dórea, J. G. Environmental Exposure to Low-Level Lead (Pb) Co-Occurring with Other Neurotoxicants in Early Life and Neurodevelopment of Children. *Environ. Res.* **2019**, *177*, No. 108641.
(55) Zhou, Y.; Grosse, S. D. In *Valuing the Benefits of Reducing Childhood Lead Exposure-Human Capital, Parental Preferences, or Both?*, Harvard Center for Risk Analysis "Risk Assessment, Economic Evaluation, and Decisions" Workshop 2019.
(56) Gould, E. Childhood Lead Poisoning: Conservative Estimates of the Social and Economic Benefits of Lead Hazard Control. *Environ. Health Perspect.* **2009**, *117*, 1162−1167.
(57) Sandvig, A.; Kwan, P.; Kirmeyer, G.; Maynard, B.; Mast, D.; Trussell, R. R.; Trussell, S.; Cantor, A.; Prescott, A. *Contribution of Service Line and Plumbing Fixtures to Lead and Copper Rule Compliance Issues*; American Water Works Association Research Foundation: Denver, CO, 2008.
(58) ACCLPP, In *CDC Response to Advisory Committee on Childhood Lead Poisoning Prevention Recommendations*, Low Level Lead Exposure Harms Children: A Renewed Call of Primary Prevention, Atlanta, GA, 2012.
(59) Navas-Acien, A.; Guallar, E.; Silbergeld, E. K.; Rothenberg, S. J. Lead Exposure and Cardiovascular Disease - A Systematic Review. *Environ. Health Perspect.* **2007**, *115*, 472−482.
(60) Ekong, E. B.; Jaar, B. G.; Weaver, V. M. Lead-Related Nephrotoxicity: A Review of the Epidemiologic Evidence. *Kidney Int.* **2006**, *70*, 2074−2084.
(61) Centers for Disease Control and Prevention, Biomonitoring Summary, Lead. https://www.cdc.gov/biomonitoring/Lead_BiomonitoringSummary.html.
(62) Regional Office for the Americas of the World Health Organization, Lead Contamination. https://www.paho.org/hq/index.php?option=com_content&view=article&id=8206:2013-lead-contamination&Itemid=39800&lang=en.
(63) Institute for Health Metrics and Evaluation, *GBD Compare*; University of Washington: Seattle, WA, 2019.
(64) Central Intelligence Agency. Madagascar, In The World Factbook. https://www.cia.gov/the-world-factbook/countries/madagascar/ (accessed Mar 11, 2021).
(65) Hutton, G.; Haller, L.; Bartram, J. Global Cost-Benefit Analysis of Water Supply and Sanitation Interventions. *J. Water Health* **2007**, *5*, 481−501.
(66) Khaliq, M.; Sommariva, S.; Buerck, A. M.; Rakotondrazaka, R.; Rakotoarisoa, L.; Barrett, L. J. P.; Mihelcic, J. R. Midstream Players Determine Population-Level Behavior Change: Social Marketing Research to Increase Demand for Lead-Free Components in Pitcher Pumps in Madagascar *J. Environ. Manage.* 2020. In Review.

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