IMPROVING CHILDREN'S LEAD RISK MODELLING IN A RURAL AND ACTIVE MINING COMMUNITY
AND
AN EVALUATION OF RISK COMMUNICATION IN A RURAL MINING COMMUNITY

by

Dominika Heusinkveld

A Thesis Submitted to the Faculty of the

DEPARTMENT OF ENVIRONMENTAL SCIENCE

In Partial Fulfillment of the Requirements

For the Degree of

MASTER OF SCIENCE

In the Graduate College

THE UNIVERSITY OF ARIZONA

2020

2

THE UNIVERSITY OF ARIZONA
GRADUATE COLLEGE

As members of the Master's Committee, we certify that we have read the thesis prepared by: Dominika Heusinkveld
titled: IMPROVING CHILDREN'S LEAD RISK MODELLING IN A RURAL AND ACTIVE MINING COMMUNITY AND AN EVALUATION OF RISK COMMUNICATION IN A RURAL MINING COMMUNITY
and recommend that it be accepted as fulfilling the thesis requirement for the Master's Degree.

Monica Diane Ramirez-Andreotta
Monica Diane Ramirez-Andreotta Date: Apr 24, 2020

Mark L Brusseau Date: Apr 24, 2020

Carol B Schwalbe Date: Apr 24, 2020

Final approval and acceptance of this thesis is contingent upon the candidate's submission of the final copies of the thesis to the Graduate College.

I hereby certify that I have read this thesis prepared under my direction and recommend that it be accepted as fulfilling the Master's requirement.

Monica Diane Ramirez-Andreotta
Monica Diane Ramirez-Andreotta Date: Apr 24, 2020
Major Advisor/Thesis Committee Chair
Department of Environmental Science

ACKNOWLEDGMENTS

I would like to thank my graduate advisor and Committee Chair Dr. Monica Ramirez-Andreotta for her support, knowledge, and guidance. I would also like to thank my committee members Dr. Mark Brusseau and Professor Carol Schwalbe, who were both instrumental in establishing the dual Environmental Science and Journalism degree program. Thanks also go to the Arizona Department of Environmental Quality, particularly Byron James, for their assistance and data. Finally, I would like to thank Tania Rodriguez-Chavez, M.S., Dr. Eduardo Saez, Dr. Eric Betterton, and Kyle Rine for their invaluable feedback and help as well as for providing the datasets used in my modelling.

DEDICATION

I'd like to dedicate this thesis to my family: my mother Anna for instilling in me a love of knowledge, my stepdad Mike for teaching me that anything is possible, my husband John for his patience and support during a long graduate program, and my mother-in-law Karen for her quiet understanding and affection.

TABLE OF CONTENTS

ABBREVIATIONS

ADEQ: Arizona Department of Environmental Quality

ASARCO: American Smelting And Refining COmpany

ATSDR: Agency for Toxic Substances and Disease Registry

AZDHS: Arizona Department of Health Services

BLL: Blood lead level

CDC: Centers for Disease Control

dL: deciliter

EPA: Environmental Protection Agency

GSD: Geometric standard deviation

IEUBK: Integrated Exposure Uptake Biokinetic model

MSA: Multiple source analysis

NAAQS: National Ambient Air Quality Standards

NPL: National Priorities List

UASRP: University of Arizona Superfund Research Program

ug: micrograms

ABSTRACT

Lead exposure has been shown to be harmful to humans in various settings. Lead is particularly harmful to children, in whom it can cause neurological problems, low IQ, developmental delay, and other health issues. There are no safe levels of blood lead in children. At the ASARCO Alternative Superfund site in Hayden-Winkelman, Arizona, lead exceedances in air and soil have been measured in the past 20 years. An important question is whether these lead levels can be expected to affect the health of children in the community, since those age seven and under are particularly vulnerable to the effects of lead. Over 140 children under age 11 live in Hayden and Winkelman. The majority live within a quarter mile of the smelter. In the main portion of the thesis, I used the U.S. Environmental Protection Agency's Integrated Exposure Uptake Biokinetic (IEUBK) model to estimate Hayden-Winkelman children's (age 6 months--7 years) blood lead levels using site-specific lead concentrations measured in indoor and outdoor air, soil, indoor dust, and water. Values used by the Arizona Department of Environmental Quality's airborne lead risk forecast were also evaluated in the IEUBK model to determine whether their forecasting program is useful in determining risk for children in the community when coupled with other measured lead exposures on the site. The results demonstrate that lead in dust is the major contributor to estimated blood lead levels in a simulated population of children at this site, while lead in the air does not contribute greatly to risk. In the second portion of the thesis, an analysis of the Arizona Department of Environmental Quality 's Air Lead Risk Forecast as a risk communication was performed and suggestions for further evaluation were given.

INTRODUCTION

Explanation of Thesis Format

The work done for this thesis was aimed at evaluating lead exposure risks in children living in the Hayden-Winkelman copper mining community in Arizona. The data used for the software modelling during the course of the research project was obtained from a variety of sources, including past state and federal agency environmental evaluations and data collected by researchers in the University of Arizona's Superfund Research Program (UASRP).

This thesis consists of two parts, which are given in Appendices A and B. The first, Appendix A, discusses the software modelling performed with site-specific data using the EPA's IEUBK software. The purpose of the modelling was to evaluate site-specific lead data and its contribution to lead exposure risks in children living at the Hayden-Winkelman site. Appendix B discusses the risk communication efforts by the Arizona Department of Environmental Quality that have taken place on the site and evaluates their potential effectiveness; it also suggests possible future areas of improvement.

Figures and tables, along with references, can be found at the end of each appendix.

Problem Statement

The research project consists of a risk assessment, reported in Appendix A, and concludes with a brief analysis of risk communication in this community (Appendix B). Air and soil in Hayden-Winkelman have been known to be contaminated with lead for at least two decades. An important question is whether that lead can be expected to affect the health of the community members. Since children age 7 and under are particularly vulnerable to the effects of lead, this project focused on assessing their risks in this community. Using the U.S. Environmental Protection Agency's Integrated Exposure Uptake Biokinetic (IEUBK) model, the probability of BLLs above the CDC's recommended cutoff value of 5 ug dL^{-1} was evaluated along with the effectiveness of the model in estimating Hayden-Winkelman children's blood lead levels using site-specific lead concentrations measured in indoor and outdoor air, soil, indoor dust, and water.

In addition, a risk communication action by the Arizona Department of Environmental Quality was evaluated for effectiveness. This risk communication consisted of an airborne lead forecast provided daily to subscribing community members.

PRESENT STUDY

Introduction

Lead exposure has been shown to be harmful to humans in various settings. Lead is particularly harmful to children, in whom it can cause neurological problems, low IQ, developmental delay, and other health issues. There are no safe levels of blood lead in children. At the ASARCO Alternative Superfund site in Hayden-Winkelman, Arizona, lead exceedances in air and soil have been measured in the past 20 years. An important question is whether these lead levels can be expected to impact the health of children in the community, since those age seven and under are particularly vulnerable to the effects of lead. Over 140 children under age 11 live in Hayden and Winkelman. The majority of these children live within a quarter mile of the smelter. This project focuses on assessing their risks.

The community of Hayden-Winkelman is near a group of mining and smelting operations in southern Arizona that have been operating for over 100 years. The smelter is currently owned and operated by ASARCO, Ltd. The towns are located about 90 miles southeast of Phoenix and about 70 miles northeast of Tucson. Residents in Hayden live ¼ mile from the site, while Winkelman residents are about 1 mile away.

Past evaluations of the Hayden-Winkelman community have shown that the air and soil in Hayden is contaminated with lead (Table 1.) Over the past 20 years, various public health and government agencies and the University of Arizona’s Superfund Research Program have done sampling and remediation work on the site.

Research Objectives

This thesis attempts to evaluate the effectiveness of the U.S. Environmental Protection Agency's Integrated Exposure Uptake Biokinetic (IEUBK) model in estimating Hayden-Winkelman children's (age 6 months-7 years) blood lead levels using site-specific lead concentrations measured in indoor and outdoor air, soil, indoor dust, and water. Values used by the Arizona Department of Environmental Quality's airborne lead risk forecast were also evaluated in the IEUBK model to determine whether the forecast provides an accurate representation of risk ranges for children in the community when coupled with other measured lead exposures on the site. The project also critiqued the ADEQ's air lead risk forecast and discussed how to improve risk communication to the community.

Objective 1. Evaluate the significance of site-specific lead concentrations using the U.S. EPA's IEUBK model.

Hypothesis: Site-specific lead values correspond to a modeled risk of adverse health consequences in children residing in Hayden-Winkelman.

Objective 2. Evaluate whether the ADEQ's air lead risk forecast is a valid tool in assessing children's risk of lead exposure.

Hypothesis: The low, moderate, and high risk levels communicated by ADEQ in its air lead risk forecast correspond to increasing risks of elevated blood lead levels in a simulated population of children when coupled with other site-specific environmental lead concentrations.

Objective 3. Evaluate ADEQ's air lead risk forecast as a risk communication action.

Hypothesis: The ADEQ's air lead risk forecast requires evaluation in order to determine whether it communicates risk effectively to the community.

Conclusion and Research Implications

In this project it was found that a simulated population of children living in Hayden-Winkelman is at risk of blood lead levels considerably higher than the 5 ug/dL level of concern used by the Centers for Disease Control (Tables 4 and 5). The results and sensitivity analysis performed suggest that high site-specific indoor dust lead levels are chiefly responsible for the high probability of simulated children with high BLLs. This holds true even with low outdoor and indoor air lead levels and with relatively low soil lead levels.

The research project also demonstrated that the output of the IEUBK model did not reflect actual BLLs of children sampled in the community over a period of years. The IEUBK model was particularly sensitive to high indoor dust levels, and these site-specific measures increased modeled BLL values considerably above actual biological sample BLLs. A review of the literature indicates that the IEUBK model weighs dust and soil lead concentrations heavily in its biokinetic calculations. Other studies have evaluated possible adjustments to the IEUBK model, including lowering the bioavailability rate of lead in dust and/or soil and lowering the ingestion rates.

This study confirmed that the chief contributor to lead exposure in children is household dust. Thus, agencies at Superfund sites should focus efforts not only on decontaminating outdoor soil but also on indoor lead decontamination. Risk mitigation strategies can include community education about vacuuming using HEPA filters, frequent changes of air filters on air-conditioning units, frequent wet-mopping, and (potentially) attic dust sampling for high-lead legacy dust. Indoor lead remediation should be included in the budget at any Superfund site that has residences nearby.

Based on this research project, suggestions include improving modelling of children's lead ingestion rates in the IEUBK model. The literature suggests that the EPA's soil/dust ingestion rates in children under 7 years old are the most likely source of overestimation of BLLs in the IEUBK model. Further research on this topic would likely improve the functionality of the model. Soil and dust lead bioavailability in IEUBK seems to be consistent with bioavailability in a number of studies. In addition, it is recommended that a sensitivity analysis be performed each time the IEUBK model is used.

The results demonstrate that the ADEQ's lead air forecast does not contribute to evaluating or decreasing children's risk of lead exposure at this site. The air lead concentrations, when input into the model, had little influence on the output BLLs.

An analysis of the ADEQ's risk communication (Lead Air Risk Forecast) was also completed, and suggestions were made for further evaluation. The chief recommendations were to survey both subscribers and non-subscribers to the forecast in order to determine how the communication may be improved. This analysis will be shared with the ADEQ and assistance with further evaluation will be offered.

APPENDIX A: Improving Children's Lead Risk Modelling in a Rural and Active Mining Community

Authors: Dominika Heusinkveld,[1] Mónica Ramírez-Andreotta,[1,2] Tania Rodriguez-Chavez,[3] Eduardo Saez,[3] Eric Betterton,[4] Kyle Rine[3]

[1]Department of Environmental Science, University of Arizona; [2]Mel and Enid Zuckerman College of Public Health's Division of Community, Environment & Policy, University of Arizona; [3]Department of Chemical and Environmental Engineering, University of Arizona; [4]Department of Atmospheric Sciences, University of Arizona

Prepared for: *Environmental Research*

***Corresponding Author:**

Mónica Ramírez-Andreotta, M.P.A, Ph.D.

1177 E Fourth Street, Rm. 429, Tucson, AZ 85721

Phone: 520-621-0091; Fax: 520-621-1647

Email: mdramire@email.arizona.edu

Introduction

Lead exposure has been shown to be harmful to humans (National Research Council, 1980). Lead is particularly harmful to children, in whom it can cause irreversible neurological problems, low IQ, developmental delay, social and emotional issues, ADHD, and other health issues (EPA, 2017; Gould, 2005; National Research Council, 1980). Blood lead levels (BLLs) are measured in humans to determine the level of exposure. Currently, a BLL of 5 micrograms per deciliter (ug dL^{-1}) and above is considered a level of concern by the Centers for Disease Control and Prevention (CDC, 2017):

> *This new level is based on the U.S. population of children ages 1-5 years who are in the highest 2.5% of children when tested for lead in their blood. This reference value is based on the 97.5th percentile of the National Health and Nutrition Examination Survey (NHANES)'s blood lead distribution in children. (CDC, Reference Level section, paragraphs 1 & 2, 2017)*

However, there is no safe level of lead for children or adults (EPA, 2017; Woolf et al., 2007). Children younger than 7 are particularly vulnerable (Maddaloni et al., 2005). According to the Agency for Toxic Substances and Disease Registry (ATSDR), lead is present naturally in the environment, but excessive human lead exposures are caused chiefly by human activities, such as mining, smelting, lead paint, and leaded gasoline. The 2007 ATSDR report on the toxicological profile of lead states: "Most of the high levels found throughout the environment come from human activities. Environmental levels of lead have increased more than 1,000-fold over the past three centuries as a result of human activity" (ATSDR 2007, p. 2). An evaluation of bone lead levels in pre-industrial humans showed that current skeletal lead levels are 500 to 1000 times higher in modern humans (Flegal & Smith, 1992).

One of the activities that leads to the contamination of the environment is mining (Ramirez-Andreotta et al., 2016a). Lead is released into the environment by metal mining and smelting, among other industrial activities. Lead is observed in mine tailings, mine waste, and mine wastewater as fine particulate material. In these forms, it can contaminate areas near mining sites via air (particularly in windy conditions) or water erosion.

The smelting process creates very fine particulates that contain high levels of metals and metalloids (Csavina et al., 2012; Sorooshian et al., 2012)). Fine particles below 1 um contain the largest percentage of lead (Csavina et al 2011, 2012). Spear et al. (1998) found that the fine size particles produced by smelting contained the largest amount of lead and also had the highest bioavailability. This lead can then be absorbed into the human body via inhalation or accidental ingestion (Zota et al., 2009). Mining-related dust can easily migrate indoors (Zota, 2012). Furthermore, the fine particles can be resuspended easily, causing repeated exposure risk (Csavina et al., 2012). Hu et al. (2007) estimate that 11 million Americans live within a mile of contaminated sites listed on the National Priorities List (NPL), also known as Superfund sites. Of these 11 million, 3-4 million are children under 18. Lead poisoning in children living in or near mining and smelting facilities is common (Csavina et al, 2012). Children are at particular risk of lead poisoning, as they have higher inhalation rates of lead per unit of body mass; they also tend to exhibit behaviors that put them at increased risk of ingesting lead (Zota, 2012), such as frequent hand-to-mouth activities.

Site Description

The community of Hayden-Winkelman is located in the shadow of a group of mining and smelting operations in southern Arizona. The towns are located about 90 miles southeast of Phoenix and about 70 miles northeast of Tucson (Figure 1). The nearby copper mine has been operating since about 1880. The smelter in Hayden was constructed in the early 1900s. The towns were founded in 1887 (Winkelman) and 1909 (Hayden) as company towns for mining workers (AZDHS, 2002). Currently, the mine and smelter are operated by ASARCO Grupo Mexico.

The most recent data from the U.S. Census indicate populations of 662 in Hayden and 352 in Winkelman (U.S. Census, 2018). In 2017 Hayden and Winkelman had an estimated median household income of $35,750, according to U.S. Census data. Both towns are in rural Gila County, Arizona. Residents in Hayden live ¼ mile from the site, while Winkelman residents are about 1 mile away (ATSDR Exposure Investigation, 2017).

A number of agencies have been involved in the evaluation of the contamination on the ASARCO site: the EPA, the ATSDR, the Arizona Department of Environmental Quality (ADEQ), and the Arizona Department of Health Services (ADHS). Evaluations and reports have been published from the 1990s to the present day (ADEQ: ASARCO Hayden Plant, 2018). In addition, researchers from the University of Arizona's Superfund Research Program (UASRP) have conducted measurements and studies on the site.

The ASARCO mine and smelter sites are designated as Superfund alternative sites (ATSDR Exposure Investigation, 2017). According to the U.S. EPA's Superfund Alternative Approach website:

The Superfund alternative (SA) approach uses the same investigation and cleanup process and standards that are used for sites listed on the National Priorities Listing. The SA approach is an alternative to listing a site on the NPL [National Priorities List]; it is not an alternative to Superfund or the Superfund process" (U.S. EPA Superfund Alternative Approach, 2020, par. 3).

Thus, an agreement is made between the responsible party and the EPA to address the site's issues under the following EPA criteria (U.S. EPA Superfund Alternative Approach, 2020):

- Site contaminants are significant enough that the site would be eligible for listing on the NPL (i.e., the site would have a Hazard Ranking Score (HRS) $\geq$ 28.5),
- A long-term response (i.e., a remedial action) is anticipated at the site, and
- There is a willing, capable PRP [Potential Responsible Party] who will negotiate and sign an agreement with EPA to perform the investigation or cleanup ("Threshold Criteria" section).

In addition to this agreement at the ASARCO site, there is a separate Consent Decree that was agreed to by all parties in 2015 "to resolve Clean Air Act violations at ASARCO's Hayden facility" (ATSDR Exposure Investigation, 2017, p. 5). This legal agreement

… requires the company to install new equipment and pollution control technology at the Hayden smelter, fund local environmental health projects…replace a diesel locomotive with a cleaner model, and pay a civil penalty" (U.S. EPA ASARCO Settlement, 2015 as cited in the ATSDR Exposure Investigation, 2017).

This agreement was reached because of a change in the U.S. EPA's National Ambient Air Quality Standards (NAAQS) for lead, which were decreased in 2008 from 1.5 micrograms m^{-3} to 0.15 micrograms m^{-3} (U.S. EPA Air Quality Criteria for Lead, 2008). As the ATSDR reported in 2017, "From 2012-2014, three-month rolling average lead levels at individual local air monitoring stations in Hayden and Winkelman ranged from 0.02 to 1.18 micrograms m^{-3}" (p. 6). (Table 1). In addition, the plant was not meeting current air quality standards for sulfur dioxide emissions.

History of BLL and Environmental Monitoring

A number of environmental evaluations have been conducted by various agencies in the community; these are summarized in Table 2. Additionally, the University of Arizona's Superfund Research Program (UASRP) has evaluated the site.

Air

One of the first environmental evaluations of the two communities was a public health assessment done by the ADHS in 1999 and reported in 2002 (ADHS, 2002). The report also featured environmental monitoring data, such as air quality data, soil data, and analyses of possible routes of exposure for residents. The report found that nearly all the air samples between 1993 and 1997 in Hayden exceeded the current EPA NAAQS for lead (0.15 micrograms m^{-3}).

The ADHS 2018 report also summarized air lead findings from five locations in the Hayden-Winkelman community between 2011 and 2016. Lead levels at three of the locations exceeded the NAAQS between 4 and 18 times during the five-year study period.

Soil

Soil lead levels in the 1990s exceeded the Soil Remediation Level of 400 mg kg^{-1}; the mean soil lead concentration as reported in 2002 by ADHS was 643 mg kg^{-1}. The soil lead concentrations led to remediation by the U.S. EPA in residences, alleys, and parks in the community between 2008 and 2014. According to ATSDR's 2017 report, soil lead concentrations dropped "below 400 mg kg^{-1}". Background median soil lead concentrations in Arizona have been reported between 16.6 and 30.1 ppm (Gustavvson et al., 2001). Felix et al. (2015) have demonstrated that the lead species present in soil at the Hayden-Winkelman site result from smelting activities.

Blood Lead Levels

BLL Sampling by ADHS in 1999 showed average blood lead levels of 3.6 micrograms/dL; however, only 14 children were sampled (Burgess, 1999; ADHS, 2002).

ATSDR reported in 2017 that testing by community physicians between 2003 and 2012 for children 0-16 years old led to 46 blood test results in Hayden and 86 in Winkelman. Of these 132 tests, two Hayden children had blood lead levels over 10 ug dL^{-1}, and six in Winkelman had blood lead levels between 5 and 10 ug dL^{-1} (ATSDR, 2017).

ATSDR conducted an exposure evaluation of Hayden children and pregnant women in April 2015 at the EPA's request. Free, voluntary blood lead level testing was offered to children age 9 months to 17 years, pregnant women, and women of childbearing age. In total, 83 residents from 29 households in Hayden and Winkelman were tested; 65% of these residents were children under 11 (approximately 53 children). In addition, adult participants were tested for arsenic. Results published in March 2017 showed that median BLLs in children were approximately twice that of the general U.S. population. Two children had BLLs over the CDC concern level of 5 ug dL^{-1}.

Unfortunately, during the testing phase, the ASARCO plant was shut down for routine maintenance; thus, BLLs may have been underestimated. Air quality data from time periods before and during the shutdown revealed air lead levels 7 to 8 times lower on average during the shutdown. Some sampling stations measured air lead levels as much as 18 times higher during the normal operating period compared with the shutdown (ATSDR, 2017).

A follow-up to this testing done by ADHS in 2017 found two out of 16 children tested with BLLs over 5 ug dL^{-1}. One of these children had a BLL of 16.2 ug dL^{-1}. AZDHS reported these findings in 2018 and stated that these elevated BLLs were thought to be from lead paint exposure.

ADHS also performed a review of BLLs in the zip codes of Hayden-Winkelman between 2014 and 2016. These findings were reported by ATSDR in its 2018 Health Consultation. This review looked at blood testing records for 110 children and found 8 children in the two communities with BLLs over 5 ug dL^{-1}. This finding indicates an elevated BLL rate of 7.3% as compared with 0.9% elevated BLL in Arizona during the same time period (ADHS, 2018).

The ADEQ Air Lead Forecast

It has thus been clear for some time that these communities have been subject to lead contamination, particularly in the air and soil/dust. In response, ADEQ began providing an airborne lead risk forecast in 2016 to the Hayden community (ADEQ Air Forecasting, 2018). The goal of the forecast is to communicate to Hayden-Winkelman residents what days they may expect a higher exposure to airborne lead based on the weather forecast. ADEQ has set three lead risk levels: green, yellow, and red (see Figure 2):

ADEQ explains:

> *ADEQ's risk-based lead forecast for Hayden predicts the possibility of reduced air quality due to lead. ADEQ monitors for air lead levels in Hayden according to EPA's requirements (one sample every six days). These samples, which take a month to process, are analyzed by a certified laboratory. These results are used to refine future forecasts. (ADEQ, "Air Quality Risk Forecast" section, n.d.).*

These particular exposure levels were chosen by ADEQ as follows (ADEQ, 2018, Slide 19):

- The "low" risk level was derived from the current NAAQS of 0.15 ug m^{-3} (U.S. EPA, 2016).
- The" high" risk level was calculated based on the average daily dietary intake of lead for an adult male (4.17 ug/day), obtained from Bolger, et al. (1996). The average breath volume for an adult male (500 mL) and the average respiratory rate for an adult male (20 breaths per minute) led to a calculated exposure of 14.4 m^3 air per day. Further calculation revealed that an ambient air lead concentration of 0.29 ug m^{-3} is needed to reach 4.17 ug per day; the high-risk level was therefore set at >0.30 ug m^{-3}.
- The "moderate" risk level was set between the high and low values.

Only data for an adult male exposure scenario were used by ADEQ despite the fact that children are at highest risk of adverse health effects from lead exposure. However, the ADEQ states that values were similar for different ages and genders (ADEQ, 2017, personal communication).

UASRP Research Efforts

Concomitantly, the University of Arizona Superfund Research Program (UASRP) has been monitoring the site since 2008. Studies have investigated the scale and spread of metal and metalloid contaminants originating from the smelting activities and the tailings piles (Csavina et al., 2011) and the properties of aerosols in the area (Felix et al. 2015; Sorooshian et al., 2012). The University of Arizona continued to sample indoor and outdoor air in the community from 2008 through 2020. In addition, soil samples were collected in 2019 in the community as part of Project Harvest, a co-created citizen science project through the University of Arizona in partnership with the Sonoran Environmental Research Institute. This dataset was used in the present study, along with the ADEQ's air monitoring and forecasting data. (See Methods section.)

Study Description

The research project consisted of a risk assessment. As mentioned above, air and soil in Hayden are known to be contaminated with lead. An important question is whether that lead can be expected to affect the health of the community members. Since children age 7 and under are particularly vulnerable to the effects of lead, this project focused on assessing their risks. ATSDR (2017) reported that over 140 children under 11 live in Hayden and Winkelman. The majority live within a quarter mile of the smelter. (See Figure 2.)

The risk forecast categories (low, moderate, and high) chosen by the ADEQ in its air lead risk forecast are of unclear significance when applied to lead exposure in children. Hu et al. (2008) reported that windborne lead may be a significant contaminant for small children, since the particles from tailings piles can contain extremely high amounts of toxic metals. As mentioned above, children are particularly at risk for airborne contamination, which settles in soil and onto indoor and outdoor surfaces. In an air quality analysis at an Oklahoma mine waste site, Zota et al. (2009) reported that tailings piles contribute significantly to air lead concentrations in 2.5 um (fine) particles. Another study showed that "lead concentrations in indoor air were significantly correlated with lead concentrations in both soil…and dust" (Zota et al., 2011, p. 6.

As described, the Hayden-Winkelman site has undergone ongoing environmental assessment and biomonitoring. This level of repetitive biomonitoring and continuous multi-agency involvement at Superfund sites is not typical and can be cost prohibitive. In response, the U.S. EPA along with other federal agencies developed the Integrated Exposure Uptake Biokinetic model in 1988 (Hogan et al., 1998). This software "is designed to model exposure from lead in air, water, soil, dust, diet, and paint and other sources with pharmacokinetic modeling to predict blood lead levels in children 6 months to 7 years old" (U.S. EPA, 1994, p. ii). The model is recommended for estimating lead doses in children living at Superfund sites. It can also be used as a tool for estimating changes in BLLs as exposure parameters are modified.

The U.S. EPA favors using the IEUBK model for estimating children's risks from lead exposure. By the time children have clinically elevated BLLs, they may have already suffered the health consequences. For this reason, the U.S. EPA encourages Superfund sites to use the IEUBK modelling software as a primary prevention measure (National Research Council, 2005). Superfund sites may also not be able to perform widespread BLL testing because of the lack of funds or nearby research programs or universities. In addition, the IEUBK model may be used for estimating risk of elevated BLLs at inactive industrial sites where there will be future residential development in order to inform remediation actions (Hogan et al., 1998). For these reasons, it is important to evaluate the validity of the IEUBK model at sites where BLL sampling is feasible.

Because of the ongoing oversight and biomonitoring in Hayden/Winkelman, this site provided a unique opportunity to validate the U.S. EPA's Integrated Exposure Uptake Biokinetic (IEUBK) model and determine whether it can successfully predict the percentage of elevated BLLs in children. Here, the IEUBK model was used to (1) estimate elevated blood lead levels in a hypothetical child population with the following site-specific lead concentrations and exposure parameters measured at Hayden/Winkelman: indoor and outdoor air, soil, indoor dust, and water and (2) determine whether the ADEQ's low, moderate, and high ambient air lead concentration forecast categories were safe for children, i.e., would not lead to an increased percentage of children under 7 with BLLs above 5 ug dL^{-1}.

Methods

IEUBK Model

Using the EPA's Integrated Exposure Uptake Biokinetic (IEUBK) software model, version IEUBKWin v1.1 build 11, and air and soil lead concentration data obtained from existing site datasets, this study characterizes what percentage of BLLs exceed 5 ug/dL in the simulated population of children.

The software consists of four modules (U.S. EPA Software and Users Manual for IEUBK Model, n.d.):

1. The exposure module, which uses lead concentrations in the environment and the rate at which a child inhales or ingests contaminated media to determine lead exposure; site-specific data is often used here:

   *Lead intake rate = media lead concentration * media intake rate*
2. The uptake module, which modifies the lead intake rates by using absorption factors. The model assumes a 50% absorption of lead intake from water and food and a 30% lead intake absorption from soil and dust; defaults may be changed if site-specific data are available.

   *Lead uptake rate = lead intake rate * absorption factor*
3. The biokinetic module, which estimates transfer rates for lead moving around physiological compartments and elimination pathways. This module is not alterable, being part of the program code.
4. The probability distribution module, which estimates a plausible distribution of blood lead concentrations centered on geometric mean lead concentration calculated by

biokinetic module. This module calculates the probability that a child's BLL will exceed a level of concern. Users can specify the level of concern.

For this study, the blood lead level of concern was set at 5 ug/dL. Users can also modify the Geometric Standard Deviation (GSD). This is a measure of the variability in lead concentrations in a child or population of children. The default GSD is 1.6. and should only be altered if there are large, documented, site-specific differences in child behavior or lead biokinetics. The GSD was not modified from the default value for this study. Figure 3 illustrates the components of the IEUBK model.

The IEUBK model includes lead exposure sources from air, soil, dust, drinking water, and dietary intake. Other sources, such as lead paint, may also be included. Each of these parameters has a default value; site-specific values may also be input. The IEUBK User Manual recommends against altering any default values unless site-specific data are available.

Table 4 shows the AZDHS 2002 Public Health Assessment estimates and compares them to the default values in the IEUBK model. The "Known Values" column refers to various site-specific findings by University of Arizona researchers, ATSDR, and other agencies.

Exposure Scenarios

In this research project, three scenarios were simulated in the IEUBK software using site-specific values for indoor and outdoor air, residential soil, dust, and water. These values were available from sources listed in Table 5 and were collected over several years by both UASRP and state agencies. The simulated scenarios used three different air lead concentrations and two different soil concentrations (Tables 5a and 5b)):

- Scenario 1: Air lead levels measured by the University of Arizona Superfund Research Program (UASRP).
- Scenario 2: Average of ADEQ's *forecasted* air lead concentrations. This scenario was designed to evaluate whether the forecast accurately predicts risk levels for children in the community.
- Scenario 3: Average of *measured* lead concentrations in air by ADEQ. This was used for comparison with Scenario 2 (forecasted air lead concentrations).

Ingestion: Water and Dietary Values

Water lead values were obtained from the Arizona Water Company's 2013 and 2016 water quality reports and averaged for the model. This mean was 4 ppb or ug L^{-1}, which was the same as the IEUBK's default value. The water lead concentrations were unchanged in all scenarios. The IEUBK's default values were used in each scenario for dietary lead ingestion as no site-specific values were available.

Ingestion: Soil and Dust

Dust lead concentrations were obtained from UASRP dust sampling data. Dust was collected via Microorifice Uniform Deposit Impactor (MOUDI) inside the Hayden High School, and lead content was analyzed as outlined in Csavina et al. (2011). The values used in the model were the mean of lead content in all particle sizes.

Soil data were obtained from samples obtained over two years via the University of Arizona's Project Harvest study. These samples were taken from the top 6 inches of soil from residential locations in Hayden. For Year 1, the mean soil lead content of soils from 8 samples

(66.14 ppm) was used in the model. For Year 2, the mean soil lead content was calculated as 101.7 ppm from a total of 5 samples.

Lead content in the air, soil, and dust samples obtained by UASRP was analyzed in the University of Arizona's Arizona Laboratory for Emerging Contaminants (ALEC). The ADEQ air samples were analyzed by that agency.

Inhalation: Indoor and Outdoor Air Values

Outdoor air lead concentrations used in the model were obtained from three different sources—one for each of the three exposure scenarios. In Scenario 1 the mean of outdoor air lead concentrations collected by UASRP was used. In Scenario 2 the mean of the ADEQ's lead air forecasts for the same time periods was used. Finally, in Scenario 3 the mean of actual air lead values measured by the ADEQ for the same dates as the forecast was used. This allowed for comparison of the forecast accuracy and evaluation of the usefulness of the forecast with respect to possible exposures in the community.

The indoor air lead concentration was obtained from UASRP sampling data. Air was collected via MOUDI, and lead content was analyzed as outlined in Csavina et al. (2011). Mean air lead content was calculated for particle sizes <2.5 um and converted to "percent of outdoor air," as this is the input that the IEUBK model requires.

Modeling and Outputs

The IEUBK software was run in single simulation mode. For each of the three scenarios, two runs were modeled: Run 1 used site-specific data for soil, dust, and water. In Run 2 the IEUBK's default Multiple Source Analysis (MSA) of dust lead was used in place of site-specific values. The MSA is based on air and soil lead concentrations; thus it varied slightly for each scenario (Tables 5a and 5b). A site-specific concentration of soil lead of 1163 ppm was used in Run 1.

Once the above inputs were entered, the IEUBK model output a BLL distribution curve and a geometric mean for each scenario and run. The percentage of children with BLLs above the level of concern (set at 5 ug dL^{-1}) was also resulted by the model. These results are shown in the tables and figures section (Tables 6 and 8 and Figure 4).

To determine the relative contribution of air, soil, and dust values to the overall risk in the simulated population, a sensitivity analysis was done. Tables 9, 10, and 11 show the inputs into the IEUBK model to determine the effect of changing air, soil, and dust values (respectively) by a factor of 10 on the geometric mean and percentage of children with BLL over 5ug dL^{-1}. The remainder of the inputs into the model (water, food) were as reflected in Table 5 and were kept the same for all runs.

Results

The results of Run 1, which used site-specific dust concentrations in the IEUBK inputs, indicate that a simulated population of children living in Hayden-Winkelman is at risk of BLLs considerably higher than the 5 ug dL^{-1} level of concern designated by the CDC. (Table 6 and Figure 4.) Over 80% of children have high BLLs in this particular simulation. This holds true despite low outdoor and indoor air lead concentrations and relatively low soil lead concentrations.

The differences in soil lead concentration from samples in Year 1 (66.14 ppm) and Year 2 (101.7 ppm) made a slight difference in the resulting BLLs. In Run 1, the percentage of children with BLLs above the 5 ug dL^{-1} cutoff was 80.6% for Year 1 soil lead concentrations and 81.6% for Year 2 soil lead concentrations.

The results of this simulation are at odds with blood samples obtained at the site (Table 2 and Table 7), which indicate that only a small percentage of children tested in the community in the past have had elevated BLLs in various screening tests run by different agencies over a multi-year time period (1999-2016). In past community-based BLL testing, the percentage of children with BLLs over 5ug dL^{-1} ranged between 1.5% and 15.4% with an average of 7%. While this is a considerable range, it does not come close to the 80.6% obtained in the simulation. Thus, in Run 2, the simulation was run again, using lower values for indoor dust.

Run 2 used the IEUBK's default Multiple Source Analysis (MSA) for dust concentrations instead of site-specific dust values. (See Table 6 and Figure 4.) In the MSA selection the software runs a simulation based on the air and soil lead concentrations. In this community, soil lead concentrations were relatively low in site-specific samples, possibly due to prior remediation efforts.

With lower indoor dust concentrations used for the input, the geometric mean of BLLs in the simulated population fell well below the level of concern. (See Table 8.) The percentage of children in the simulated population whose BLLs were above 5 ug dL^{-1} was low. For Run 2, Year 1 soils returned 0.35-0.53 % and Year 2 soils returned 1.26-1.68% children with BLLs above the cutoff. This represents roughly a doubling of the percentage from Year 1 to Year 2 soil levels. This result was seen for all three concentrations of air lead input into the model. Figure 5 shows this information in graph form.

Neither Run 1 nor Run 2 thus reflects the BLL values in biological samples obtained from children living in Hayden-Winkelman. This discrepancy raises a number of questions and will be discussed in the next section.

In the sensitivity analysis, increasing the air lead input by ten-fold made little difference to the BLL geometric mean (Table 9). Increasing the soil lead input by a factor of 10 roughly doubled the BLL geometric mean (Table 10). Increasing the dust lead input by a factor of 10 resulted in a roughly ten-fold increase in BLL geometric mean in the model (Table 11).

Discussion

The results of Run 1 in the IEUBK model (input of site-specific dust lead concentrations) indicate that a simulated population of children living in Hayden-Winkelman is at risk of 81% of children ages under 7 years having BLLs considerably higher than 5 ug dL^{-1}, the level of concern specified by the CDC. This result is despite low site-specific outdoor and indoor air lead concentrations and relatively low soil lead concentrations. The result demonstrates that current measured lead concentrations in dust result in elevated BLLs in the IEUBK model, which would in turn lead to adverse health consequences in children in the Hayden-Winkelman community.

The sensitivity analysis shows that the increased BLL values output by the IEUBK model are independent of air lead concentrations and are chiefly driven by dust lead concentrations, and to a smaller extent by soil lead concentrations. This is because the model's design is based on observations that ingestion is the chief exposure pathway in children (Figure 3). Laidlaw et al. (2017) stated that, in various Australian studies, "the strongest associations for BLL were interior house dust and soil" and that "house dust is recognized as probably the most significant contributor to BLLs in children" (p. 787 and 788).

Cornelis, et al. (2006) demonstrated that the IEUBK model did not respond to changes in lead concentration in air. Other studies have shown that the IEUBK model highly favors the indoor dust and soil lead components and tends to overestimate BLL values when these two sources are high in lead (Cornelis, et al. 2006; Hilts, 2003; von Lindern, et al. 2016). These three studies found the overestimation to be greatest in populations whose BLL geometric means were lower than 10 ug dL^{-1}.

The literature suggests various reasons for this overestimation. The first is that the bioavailability values estimated by the IEUBK model may be excessive. This hypothesis has been discussed in a number of studies (Hilts, 2003; von Lindern, et al., 2016; Cornelis, et al. 2006). Table 13 shows five studies which have attempted to determine the bioaccessibility of lead in dust and/or soil in contaminated sites. The average bioaccessibility in the studies ranges from 16-38%, with the majority being 28-38%. This shows good agreement with the IEUBK's default value of 30%.

Some studies have used lower ingestion rates (IRs) for lead than the IEUBK default of 105 mg/day (Table 14). Cornelis, et al. (2006) used Flemish IR estimations of 75 mg/day and noted that, in their study, "a substantial overestimation [of BLLs] would have been found if the [IEUBK] model's default soil ingestion values would have been used" (p. 976). In their study of urban lead exposures in Sydney, Australia, Laidlaw, et al. (2017) used IRs of 25-100 mg/day, depending on the type of site (residential, industrial, etc). Von Lindern, et al. (2016) ran four lead ingestion scenarios and found that IRs of 67-93 mg/day for children under 3 and 51-65 mg/day for children 3-7 are likely more accurate. These studies suggest that the overestimation of BLLs from high dust and soil lead values may be due to overestimation of ingestion rates in the model. Finally, Brattin and Griffin (2011) have postulated that the average mass fraction of soil in dust (Ksd) is overestimated in the IEUBK model.

The question arises whether indoor dust concentrations on the site can be as high as 1163 ppm when soil lead concentrations are relatively low. Von Lindern, et al. (2016) noted that house dust lead concentrations remained high even a decade after outdoor soil cleanup efforts at a Superfund site in Idaho. Thus, it is plausible that house dust levels in Hayden-Winkelman still exhibit greatly elevated lead concentrations despite remediation efforts. Other studies which have investigated dust lead concentrations at similar sites have found residential dust lead concentrations with extreme ranges from 109 ppm to 73, 394 ppm (Table 12). Furthermore, these authors observed a very broad intra-study range of dust lead (Argyraki, 2014; Cornelis, et al. 2006; Hilts, 2003; von Lindern, et al., 2016; Zheng, et al. 2013; Zota, et al., 2011). These broad ranges suggest considerable uncertainty in measured dust lead concentrations in residences.

Site-specific reasons for elevated indoor dust lead may be from lead paint inside the homes, the presence of legacy dust in the building, instrument error, sampling error, or an unidentified factor. Hu et al. (2008) found that lead paint in homes near a lead and zinc mining contamination site in Tar Creek, Oklahoma, did not have a significant impact on blood lead concentrations in children. That study also discussed that fine dust particles contain lead concentrations much higher than larger particles, a finding supported by Carrizales et al. (2006). Other studies have reported that lead concentrations in indoor dust may be 2-5 times higher than in soil (Argyraki, 2014; Zheng et al., 2013; Brattin & Griffin, 2011; Cornelis, 2006). As Argyraki (2014) and Csavina et al. (2012) point out, fine dust particles are more easily picked up on the skin and ingested. The relative enrichment in lead in fine dust poses a double risk to small children and confirms that indoor dust is a critical exposure pathway for children, a finding supported by Zheng et al. (2013). Thus, the indoor dust lead concentration used in this study is plausible.

It is significant to note that the percent of children with elevated BLLs returned by the IEUBK simulations do not match the biological data from children in the community. The high lead dust simulation (Run 1) returns much higher percentages than do the biological data, while the low lead dust simulation (Run 2) returns extremely low percentages, near zero. This may be due to a number of factors. As already discussed, the IEUBK model tends to weigh dust lead concentrations more heavily than air and other environmental sources. The relatively high concentrations of lead in indoor dust in the samples collected at the local high school may have skewed the simulation toward the 81% elevated BLL percentage. This is borne out by the results of Run 2, in which the model's Multiple Source Analysis calculations are used in place of site-specific dust lead concentrations. The MSA calculated indoor dust concentrations were between 47.4 ppm and 86.2 ppm (see Tables 5a and b for MSA dust lead values). The average percentage of children with BLLs over 5 ug dL^{-1} in the community samples is 7.0% (Table 7). This matches best with the dust lead concentration of 200 ppm in the sensitivity analysis in Table 11, which returns a percent BLL>5 ug/dL of 5.2%. As noted in Table 12 and discussed above, other studies (particularly Argyraki, 2014; Cornelis, et al., 2006; von Lindern, et al. 2016, and Zheng, et al., 2013) have observed large variations in on-site indoor residential dust lead concentrations. This uncertainty may account for the difference between measured and predicted BLLs.

The biological samples from the community may also not be representative; the studies in which blood was sampled directly by the agencies had small sampling populations (13, 14, and 53 children; see Table 2). The larger samples listed in agency reports (110 and 152 children) were from a review of BLLs in children living in affected zip codes tested by physicians in surrounding communities. These larger datasets may not reflect adequate sampling of the children in Hayden-Winkelman or those living within the site boundary or within one mile of the site. The zip code BLL datasets are also subject to potential testing and sampling errors, since they are a conglomeration of BLLs taken in the larger community, under (one assumes) different circumstances and processed by different testing agencies. However, given the amount of environmental monitoring occurring in the community, it seems unlikely that an epidemic of elevated BLLs in 80% of local children has been missed.

Based on this study, some recommendations can be made with regard to using the IEUBK model. As per the above discussion, the soil and dust ingestion rates are the best target for correction, since measured bioaccessibility values were close to the IEUBK default in several studies. Von Lindern, et al. (2016) suggested that lead ingestion rates should be reduced by 40% from the IEUBK defaults to more closely match actual BLLs. Cornelis, et al. (2006) also found that the model's default soil ingestion values result in overestimation of BLLs; their soil ingestion values were set at 71% of the IEUBK model default. Lowering the ingestion rates in the model might result in a more accurate prediction of BLLs in a Superfund community's children. However, this would need to be verified through further studies using both IEUBK modelling and BLL sampling for comparison. Cornelis, et al. (2006) went as far as to recommend that "the IEUBK model should not be run to predict actual blood lead levels without the availability of blood lead level measurements" (p 980).

Carrizales, et al. (2006) reported good correlation between IEUBK modeled BLLs and measured BLLs at a mining site in Mexico. The geometric mean BLLs in that study were 14.8 ug dL^{-1} (actual) and 16 ug dL^{-1} (IEUBK). Cornelis et al., (2006) also found good agreement of the geometric mean BLLs between IEUBK predicted and measured values. It is possible that the IEUBK model is more accurate in predicting higher BLL ranges rather than at lower ranges. Cornelis, et al. (2006); Hilts, (2003) and von Lindern, et al. (2016) found the overestimation to be greatest in populations whose BLL geometric means were lower than 10 ug dL^{-1}. Cornelis, et al. stated that "the highest relative overestimation [in BLL] is found…where the children have the lowest lead exposure" (Cornelis et al., 2006, p. 974). Furthermore, as Mickle (1998) states in his article on validation of the IEUBK model, "The identification of those parameters that have the most impact on the result" is critical (p. 1533). Thus, a sensitivity analysis should be done whenever the model is used.

Initial validation studies of the IEUBK model have shown it to be fairly accurate (e.g., Hogan, 1998; Zaragoza & Hogan, 1998). These validations were done for a BLL cutoff of 10 ug dL^{-1}. It may be useful to validate the model for BLLs near the current cutoff of 5 ug dL^{-1} and below. It is important to recall, however, that even BLLs below the 5 ug dL^{-1} level of concern are likely to be harmful to children. Lanphear et al. (2005) demonstrated that lead-associated effects on IQ were greater for children with relatively low BLLs (below 7.5) than in children with higher BLLs. Numerous studies have also shown that there is no safe lead BLL and that the effects of chronic, low-level lead exposure has been linked to neurological deficits, ADHD, hypertension, heart disease, kidney disease, and stroke, among others (Gould, 2009).Thus, even the relatively low BLLs obtained by direct sampling in this community are cause for concern.

Because this and other studies have shown that the chief contributor to lead exposure in children is household dust, agencies at Superfund sites should focus efforts not only on decontaminating outdoor soil but also on indoor lead decontamination. Risk mitigation strategies can include community education about vacuuming using HEPA filters, frequent changes of air filters on air-conditioning units, frequent wet-mopping, and (potentially) attic dust sampling for high-lead legacy dust. Indoor lead remediation should be included in the budget at any Superfund site that has residences nearby.

Limitations

Limitations inherent in this study include the fact that only a small number of samples of site-specific data, particularly soil lead concentrations, were available from residential areas

(N=8 soil samples from Year 1 and N=5 in Year 2). Perhaps more importantly, the samples were gathered from the top 6 inches of soil; most studies investigating soil lead exposures in children take samples from the top 1-3 cm of soil only (Laidlaw, et al. 2017), as this is the soil with which children are most likely to come into contact. In addition, as mentioned above, more biomonitoring samples from children in the community would have been helpful in evaluating the effects of environmental lead levels on BLLs.

Limitations of the IEUBK model, which predicts a much higher effect on BLLs from dust and soil than from other sources (particularly air), also may have affected results, as discussed above. The studies mentioned above that have used and evaluated the IEUBK model have observed this tendency (Bratten & Griffin, 2011; Hilts, 2003; von Lindern, et al., 2016; Laidlaw, et al., 2017).

A major limitation in this study is that in this dataset, lead indoor dust concentrations were collected at the high school and thus may not provide a representative sample of a child's residence. The IEUBK user manual recommends that dust lead concentrations be obtained from areas frequented by children inside the house. Dust levels in the elementary school would have been more age-appropriate, but these were not available.

Conclusion

This study offers an opportunity to evaluate the Hayden-Winkelman community's risk of elevated BLLs in children residing there. It also allows for comparison of the IEUBK model outputs with previous biological testing for lead done in the area.

This study's findings of high BLLs in a simulated population of children are chiefly dependent on the measured indoor dust levels, which were not measured in homes but in a high school. It is thus unclear whether this information is of use to the community in terms of risk management. Future studies on this site should aim to collect dust directly from residences via low-flow rate vacuum as recommended in the IEUBK Users Manual (U.S. EPA, n.d.). Since the simulation showed that air lead did not significantly contribute to children's BLLs in the model, the ADEQ's air lead risk forecast has limited usefulness as a risk assessment tool for lead exposure in children in Hayden-Winkelman. However, education in the Hayden-Winkelman community on indoor dust reduction and strategies on improving indoor air quality will likely be beneficial.

The IEUBK model, while useful, has some limitations, as discussed above. Future studies evaluating its validity in more communities and comparing IEUBK projections with actual BLL samples would help determine where the model could be improved. In particular, it would be helpful to determine the model's validity at BLL values below 10 ug dL^{-1}, since even low BLLs have been shown to adversely affect children's health and well-being.

***Acknowledgments**:*

I would like to thank Tania Rodriguez-Chavez, M.S.; Dr. Eduardo Saez, Dr. Eric Betterton, and Kyle Rine for their invaluable feedback and help as well as for providing the datasets used in my modelling. I would also like to thank ADEQ staff, particularly Byron James, for providing helpful data and information.

APPENDIX A FIGURES AND TABLES

Figure 1: Map and satellite view of the Hayden-Winkelman community. Google (2019)

Table 1: Hayden, AZ air quality data, 1993-1997. Adapted from Arizona Department of Health Services Public Health Assessment, ASARCO Hayden Smelter Site; Hayden, Arizona, 2002 and U.S. EPA Air Quality Criteria for Lead, 2008.

Year	Annual Average ug m^{-3}	Lead NAAQS before 2008 ug m^{-3}	Lead NAAQS after 2008 ug m^{-3}	Exceeds Current NAAQs?
1993	0.09	1.5	0.15	No
1994	0.34	1.5	0.15	Yes
1995	0.35	1.5	0.15	Yes
1996	0.30	1.5	0.15	Yes
1997	0.37	1.5	0.15	Yes

Table 2: Summary of reported lead levels in past Hayden/Winkelman environmental and biological samples.

Agency; Year	Sample Type	Results
	Environmental Samples	
ADEQ; 1994-1997	Air	0.30-0.37 ug m^{-3}
ATSDR, 2018	Air	0.130-0.199 ug m^{-3}
ADHS; 2002	Soil	643 mg/kg (average)
	Biological samples -Blood	
AZDHS,2002	14 children	3.6 ug dL^{-1} average
ATSDR, 2015	83 residents (65% children 1-11 or approx. 53 children)	2 children over 5 ug dL^{-1}; Median levels 2x higher than US population
ATSDR 2017; measurements from 2003-2012	46 children in Hayden and 86 in Winkelman	2 children in Hayden over 10 ug dL^{-1} 6 children in Winkelman over 5 ug dL^{-1} 7.3% compared to 0.9% statewide
Community blood testing ATSDR 2018	110 children underage 16	8 children over 5 ug dL^{-1}
ATSDR 2018	13 children under age 16	2 children over 5 ug dL^{-1}

Figure 2: ADEQ's lead risk forecast categories. (ADEQ, *Air forecasting*, n.d.)

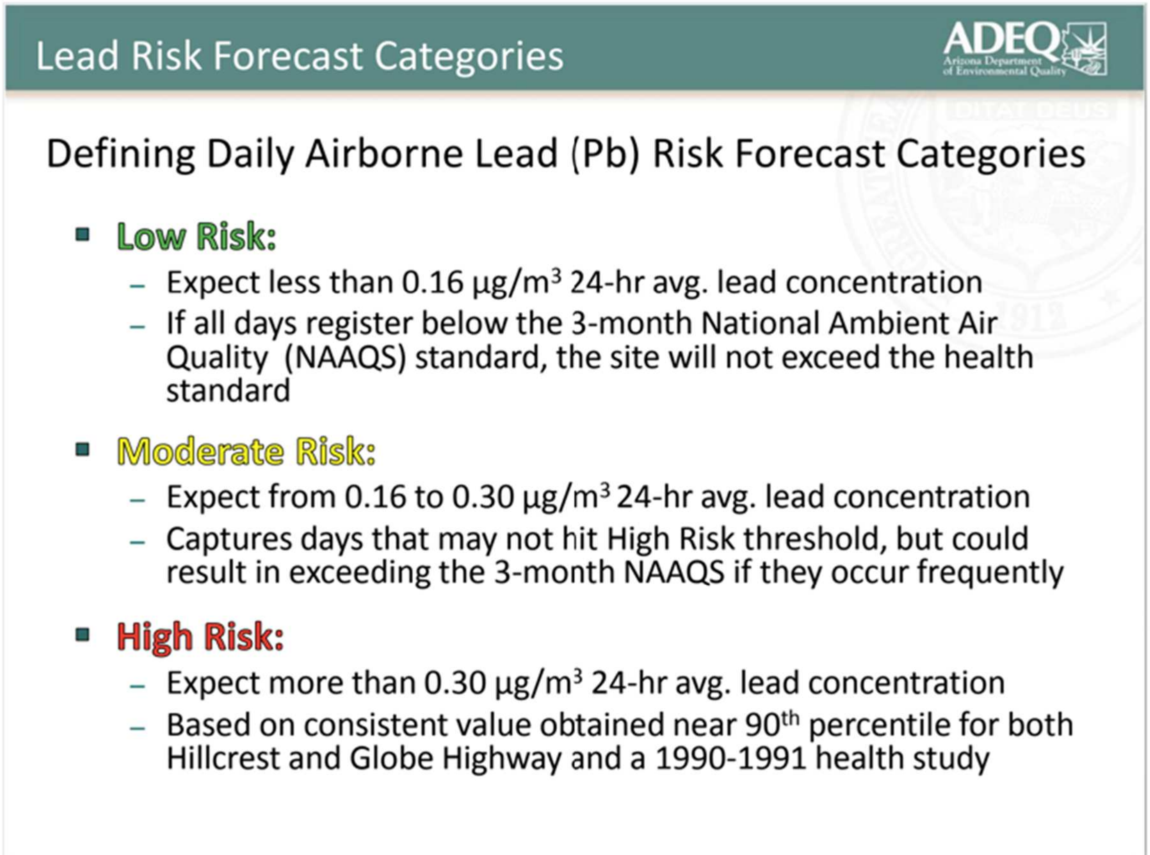


Table 3: Selected demographics of Hayden and Winkelman. (ATSDR, 2017)

Measure	Total Population	Children 0-5	Children 6-11
Hayden	662	50	52
Winkelman	353	24	20
Hayden and Winkelman	1015	74	73
Within site boundary	630	47	52
Within 1 mile of site	1041	76	76

Figure 3: Components of the EPA's Integrated Exposure Uptake Biokinetic Model, showing environmental exposure sources and pathways, absorption compartments, critical body tissue compartments, and elimination pathways. From EPA IEUBK Guidance Manual for IEUBK, n.d.

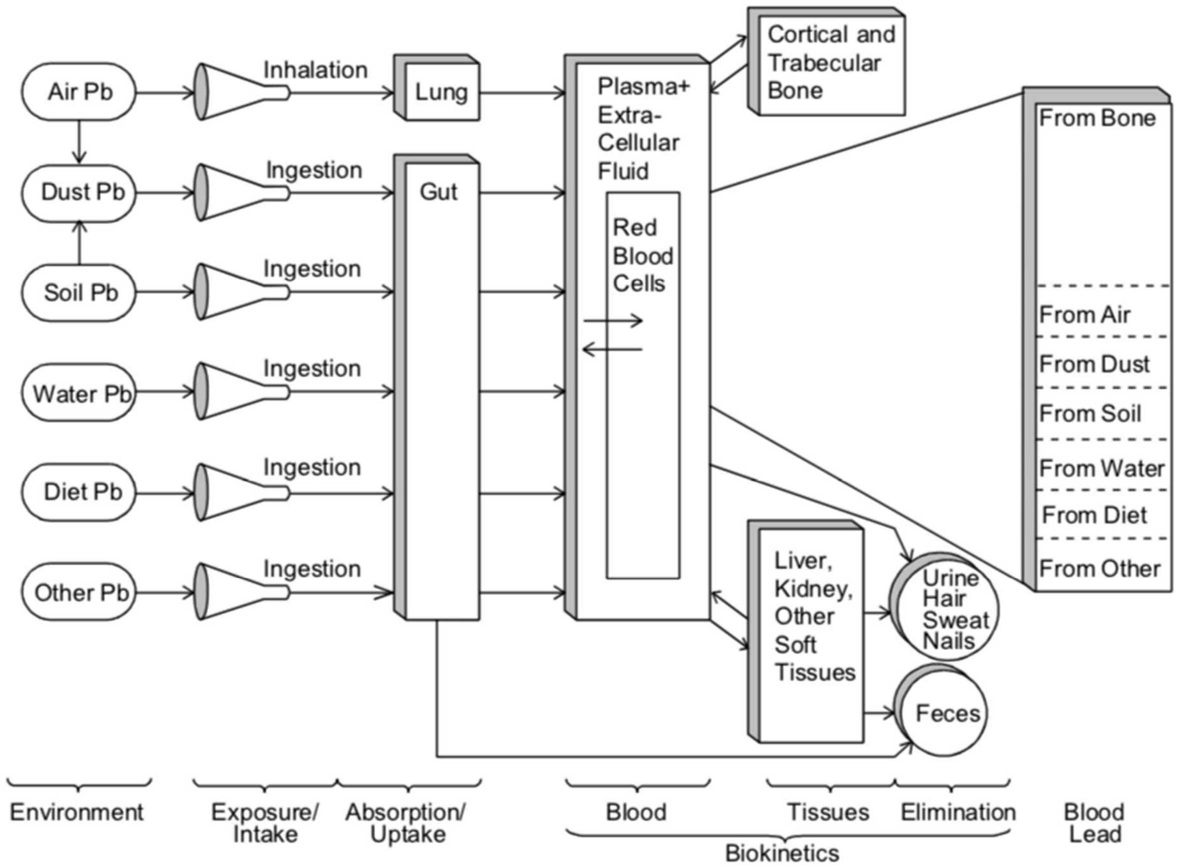


Table 4: Comparison of values in ATSDR scenario and IEUBK model default values with known values reported by various agencies.

Medium	IEUBK Model Default Lead Concentration	ADHS (2002) Lead Concentration	Site-specific Values, UA SRP
Outdoor Air	0.1 ug/m^3	0.366 ug/m^3	See Table 5
Indoor Air	Percentage of outdoor; default is 30%	0.03 ug/m^3	See Table 5
Food	Varies by age group	5 ug/day	None
Water	4 ug/day	4 ug/day	Hayden: < 4 ug/L Winkelman: 1 ug/L[b]
Soil	200 ug/g	29 mg/kg (ppm)	643 mg /kg [c] Range 3.5-1,230 ppm Average: 617 ppm before remediation [d]
Indoor Dust	200 ug/g OR Multiple Source Analysis (dependent on soil concentration)	70 mg/kg (ppm)	See Table 5

Table 5a: Scenarios and mean values input for Run 1 and 2 into the IEUBK model with Year 1 soil Pb concentrations.

				Run 1	Run 2					
Scenario	Outdoor Air Pb (ug m^{-3})	Indoor Air Pb (ug m^{-3})	Indoor Air as % of Outdoor Air	Site-specific dust Pb (ug/g or ppm)	Model MSA calculated dust Pb (ug/g or ppm)	Soil Pb (ppm)	Water Pb (ppb)	Food Pb	Blood lead level cutoff (ug dL^{-1})	GSD[7]
1.Air Pb collected by UA	0.011[1]	0.0056[1]	50.9	1163[2]	47.4	66.14[5]	4[6]	Default	5	1.6
2.ADEQ air Pb forecast	0.10[3]	0.0056	5.2	1165	56.3	66.14	4	Default	5	1.6
3.ADEQ air Pb	0.15[4]	0.0056	3.5	1163	61.3	66.14	4	Default	5	1.6

Table 5b: IEUBK model inputs with Year 2 soil Pb concentrations.

				Run 1	Run 2					
Scenario	Outdoor Air Pb (ug m^{-3})	Indoor Air Pb (ug m^{-3})	Indoor Air as % of Outdoor Air	Site-specific dust Pb (ug/g or ppm)	Model MSA calculated dust Pb (ug/g or ppm)	Soil Pb (ppm)	Water Pb (ppb)	Food Pb	Blood lead level cutoff (ug dL^{-1})	GSD[7]
1.Air Pb collected by UA	0.011[1]	0.0056[1]	50.9	1163[2]	72.3	101.7[5]	4[6]	Default	5	1.6
2.ADEQ air Pb forecast	0.10[3]	0.0056	5.2	1165	81.2	101.7	4	Default	5	1.6
3.ADEQ air Pb	0.15[4]	0.0056	3.5	1163	86.2	101.7	4	Default	5	1.6

[1] Mean of MOUDI data; <2.5 um particle size. From Rodriguez-Chavez, et al., Nov. 2016-Dec 2017; unpublished data
[2] Mean of MOUDI data; all particle sizes. From Rodriguez-Chavez, et al., Nov. 2016-Dec 2017; unpublished data
[3] Mean of ADEQ air lead forecast values, Feb. 2017-Mar. 2018
[4] Mean data from ADEQ instruments, Hillcrest site, Feb 2017-Mar. 2018
[5] Mean Pb residential soil value, Hayden, 2018; M. Ramirez-Andreotta; unpublished data
[6] Mean from Arizona Water Co. Water Quality Report, 2013 and ATSDR 2017 report
[7] Geometric Standard Deviation

Table 6: Run 1 results, reflecting the inputs shown in Tables 5a and 5b and site-specific lead dust values of 1163 ppm. Year 1 soil value results are shown in shaded columns.

Scenario	Outdoor Air Pb (ug m^{-3})	Geometric Mean (ug dL^{-1}) Year 1 Soil Pb	Geometric Mean (ug dL^{-1}) Year 2 Soil Pb	% of children above 5 ug dL^{-1} cutoff Year 1 soil Pb	% of children above 5 ug dL^{-1} cutoff Year 2 soil Pb
1.Air Pb data collected by UASRP	0.0111 [a]	7.50	7.64	80.6	81.6
2.ADEQ air Pb forecast	0.10 [b]	7.50	7.64	80.6	81.7
3.ADEQ air Pb measured	0.15 [c]	7.51	7.65	80.6	81.7

[a] Mean of MOUDI data; <2.5 um particle size. From Rodriguez-Chavez, et al., Nov. 2016-Dec 2017; unpublished data
[b] Mean of ADEQ air lead forecast values, Feb. 2017-Mar. 2018
[c] Mean data from ADEQ instruments, Hillcrest site, Feb 2017-Mar. 2018

Table 7: Percentages of children with BLLs over the 5ug dL^{-1} cutoff in the Hayden-Winkelman community based on biological samples. Please refer to Table 2 for specific sources of data.

Year(s) tested	Number with elevated BLLs/Total number tested	Age range of tested children	Percent with elevated BLLs over 5 ug dl^{-1}
2003-2012	2/132	unknown	1.5
2014-2016	8/110	<16	7.3
2015	2/53	1-11	3.8
2017	2/13	<16	15.4
Average Percentage			**7.0**

Table 8: Run 2 results for the three scenarios, reflecting inputs in Table5a and 5b and the IEUBK's Multiple Source Analysis (MSA) default for lead dust. Year 1 soil Pb results are shown in orange shaded columns.

Scenario	Outdoor Air Pb (ug m^{-3})	Geometric Mean (ug dL^{-1}) Year 1 Soil Pb	Geometric Mean (ug dL^{-1}) Year 2 Soil Pb	% of children above 5 ug dL^{-1} cutoff Year 1 soil Pb	% of children above 5 ug dL^{-1} cutoff Year 2 soil Pb
1.Air Pb data collected by UASRP	0.0111 [a]	1.405	1.75	0.35	1.26
2.ADEQ air Pb forecast	0.10 [b]	1.468	1.81	0.46	1.52
3.ADEQ air Pb measured	0.15 [c]	1.503	1.84	0.53	1.68

[a] Mean of MOUDI data; <2.5 um particle size. From Rodriguez-Chavez, et al., Nov. 2016-Dec 2017; unpublished data

[b] Mean of ADEQ air lead forecast values, Feb. 2017-Mar. 2018

[c] Mean data from ADEQ instruments, Hillcrest site, Feb 2017-Mar. 2018

Figure 4: Percentage of children with BLLs above the CDC's cutoff with comparison of the values from community blood testing, Run 1, and Run 2. Year 1 and Year 2 soil lead concentrations displayed.

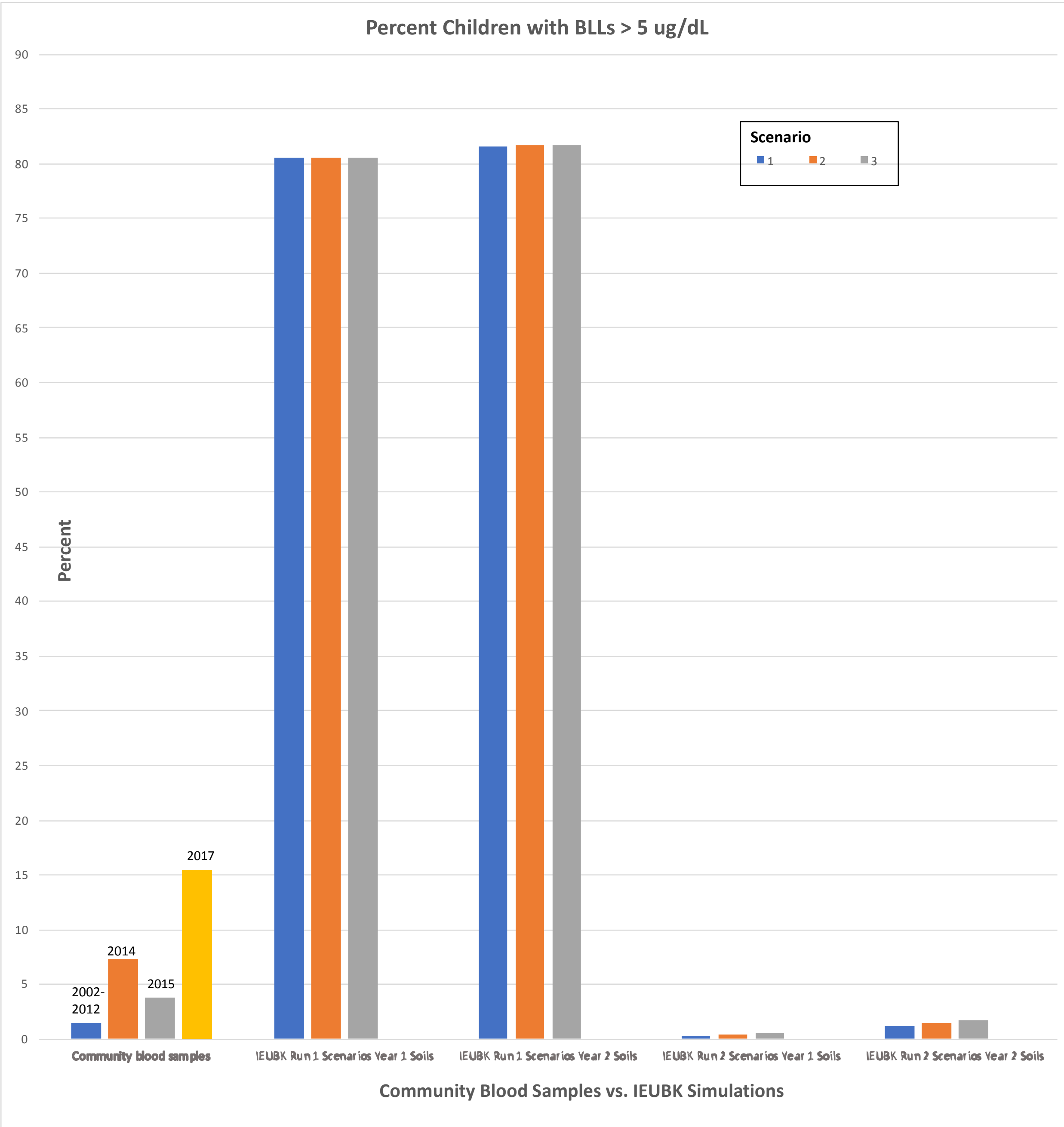


Table 9: Sensitivity analysis data with air Pb concentration as the variable. There is little change in the geometric mean.

Outdoor Air ug/m3	Indoor air/%	Soil ppm	Dust ppm	Geo mean	% BLL>5
0.01	.0056/56	60	200	2.32	5.15
0.1	.0056/5.6	60	200	2.33	5.21
1.0	.0056/0.56	60	200	2.39	5.84

Table 10: Sensitivity analysis data with soil Pb concentration as the variable. The geometric mean increases by a factor of two.

Outdoor Air	Indoor air/%	Soil	Dust	Geo mean	% BLL>5
0.1	.0056/5.6	**6**	200	2.06	2.95
0.1	.0056/5.6	**60**	200	2.33	5.21
0.1	.0056/5.6	**600**	200	4.86	47.5

Table 11: Sensitivity analysis data with Dust Pb concentration as the variable. The geometric mean increases by a factor of 10.

Outdoor Air	Indoor air/%	Soil	Dust	Geo mean	% BLL>5
0.1	.0056/5.6	60	**20**	1.20	0.12
0.1	.0056/5.6	60	**200**	2.33	5.21
0.1	.0056/5.6	60	**2000**	11.11	95.5

Table 12: Indoor dust concentrations and comparison of BLLs and IEUBK model results in selected studies using the IEUBK model at mine and smelter sites 2003-2016.

Study and location	# of samples	Indoor dust (ppm)	BLL Geometric means	IEUBK Simulation Results
Argyraki (2014) Stratoni, Greece Sulphide ore mine	30	1660 ± 1,550	No site-specific BLL data available	61% >10 ug/dL Geometric mean: 12.6±5.2
Cornelis, et al. (2006) Hoboken, Belgium Lead smelter	27	Mean: 3,275 Range: 234 to 73,394 ppm (depending on distance from site; averages from the different location zones ranged from 1287 to 6344 ppm))	GM: 4.83-18.3	IEUBK predictions within 1 ug/dL ; highest disparity is in area of lowest BLLs where IEUBK overpredicts BLLs by 10%
Hilts (2003) Trail, British Columbia, Canada Lead-zinc smelter	32	1996: 758 1995: 583 2001: 580	1996: 11.5 1999: 5.9 2001: 4.7	Geometric Means: 1996: 10.5 1999: 9.0 2001: 9.2
Von Lindern, et al. (2016) Bunker Hill, Idaho, U.S. Lead smelter	193	996 ±1,472 (House dust contributed 16-22% to BLLs)	Range 3.7 to 6.3 depending on site BLLs ranged 2.47 to 10.56 over 15 years	IEUBK consistently overpredicted BLLs in more than 50% of resident children
Zheng, et al. (2013) Lake Eyrie Basin, Australia Lead mine and smelter	19	873±657	No BLL measurements available	Geometric Mean: 3.5; Range 1.5 to 7.1

Table 13: Gastric lead bioaccessibility values in dust and/or soil from recent studies of contaminated sites. The default IEUBK bioavailability of lead in soil and dust is 30%.

Study, Location, and Mine Type	Bioaccesibility/bioavailability of lead (mean)
Argyraki (2014) Strattoni, Greece Sulphide ore mine	Soil: 33% Dust: 38%
Carrizales, et al. (2006) San Luis Potosi, Mexico Copper smelter	Soil: 32%
Laidlaw, et al. (2017) Sydney, Australia Urban site	Soil: 34%
Manjon, et al. (2020) Nevada County, California, U.S. Former gold mining site	Soil: 8%
Thomas, et al. (2018) Humboldt, Arizona, U.S. Mine site	Dust: 13.3% (0.18 to 61.4 %)
Von Lindern, et al. (2016) Bunker Hill, Idaho, U.S. Lead smelter	Soil: 33% Dust: 28%
Zheng, et al. (2013) Lake Eyrie Basin, Australia Lead mine and smelter	Soil: 20%±5% Dust:16%±7%

Table 14: the IEUBK model ingestion rate values from selected studies.

Study and location	Ingestion Rates (mean, mg/d)	Effect of adjustment on BLL prediction
Cornelis, et al. (2006) Hoboken, Belgium Lead smelter	75 (age range 1-7 years, Flemish ingestion rates)	• IEUBK predictions within 1 ug/dL. • Highest disparity is in area of lowest BLLs where IEUBK overpredicts BLLs by 10% • Using default IRs would have resulted in substantial overprediction by the IEUBK model
Laidlaw, et al. (2017) Sydney, Australia Urban (multiple site types)	25-100 (0-7 years old Australian ingestion rates, value used depended on type of site)	• Effects of IR changes on IEUBK predictions were not reported
Von Lindern, et al. (2016) Bunker Hill, Idaho, U.S. Lead smelter	Four ingestion scenarios run 67-93 (0-3years old) 51-65 (4-7 years old)	• Authors recommended reducing IRs by 40% in IEUBK model

Note: The default IEUBK IR is 105 mg/d.

APPENDIX A REFERENCES

1. Arizona Department of Environmental Quality (2019). *Air forecasting.* Retrieved March 30, 2020 from http://www.azdeq.gov/air-forecasting

2. Arizona Department of Environmental Quality: Hayden-Winkelman Daily Airborne Lead Risk Forecast Methodology. Community presentation, 2017. Personal communication.

3. Arizona Department of Environmental Quality (2019). *Superfund Alternative Site* | ASARCO Hayden Plant. Retrieved March 27, 2020 from https://azdeq.gov/node/1871

4. Argyraki, A. (2014). Garden soil and house dust as exposure media for lead uptake in the mining village of Stratoni, Greece. *Environmental geochemistry and health*, *36*(4), 677-692.

5. Arizona Department of Health Services (May 2018). Arizona Department of Health Services Health Consultation: Evaluation of Community Exposure to Lead and Sulfur Dioxide in Air. Hayden and Winkelman Communities. https://www.atsdr.cdc.gov/HAC/pha/haydenWinkelman/ADHS_Hayden_Air_HC-508.pdf

6. Arizona Department of Health Services (2002). Public Health Assessment, ASARCO Hayden Smelter Site; Hayden, Arizona. https://www.azdhs.gov/documents/preparedness/epidemiology-disease-control/environmental-toxicology/asarco-hayden.pdf

7. Agency for Toxic Substances and Disease Registry Exposure Investigation: Biological Testing for Exposure to Lead and Arsenic near Asarco Hayden Smelter Site; Hayden and Winkelman, Arizona. March, 2017. https://www.atsdr.cdc.gov/HAC/pha/AsarcoHaydenSmelterSite/AsarcoHaydenSmelterSite_HC_EI_03272017_508.pdf

8. Agency for Toxic Substances and Disease Registry: Toxicological profile for lead (2007). https://www.atsdr.cdc.gov/ToxProfiles/tp13.pdf.

9. Arizona Water Company. (2016) *Annual Water Quality Report: Winkelman, AZ.* http://www.azwater.com/files/water-quality/ccr-winkelman-2016.pdf

10. Arizona Water Company. (2013) *Annual Water Quality Report: Winkelman, AZ.* http://azwater.com/files/water-quality/ccr-winkelman-2013.pdf

11. Bolger, P., Yess, N., Gunderson, E., Troxell, T., & Carrington, C. (1996). Identification and reduction of sources of dietary lead in the United States. *Food Additives & Contaminants, 13*(1), 53-60.

12. Brattin, W., & Griffin, S. (2011). Evaluation of the contribution of lead in soil to lead in dust at superfund sites. *Human and Ecological Risk Assessment*, *17*(1), 236-244.

13. Burgess JL, Carter DE, O'Rourke MK. (2000). Hayden-Winkelman Arsenic and Lead Survey, 1999. Available at: https://assets.documentcloud.org/documents/267080/hayden-winkelman- arsenic-and-lead-survey.pdf. Accessed July 18, 2019.

14. Carrizales, L., Razo, I., Tellez-Hernandez, J. I., Torres-Nerio, R., Torres, A., Batres, L. E., ... & Díaz-Barriga, F. (2006). Exposure to arsenic and lead of children living near a copper-smelter in San Luis Potosi, Mexico: Importance of soil contamination for exposure of children. *Environmental Research*, *101*(1), 1-10.

15. CDC. (n.d.) *Lead.* Retrieved March 20, 2020 from https://www.cdc.gov/nceh/lead/

16. Cornelis, C., Berghmans, P., van Sprundel, M., & Van der Auwera, J. C. (2006). Use of the IEUBK model for determination of exposure routes in view of site remediation. *Human and Ecological Risk Assessment*, *12*(5), 963-982.

17. Csavina, J., Field, J., Taylor, M. P., Gao, S., Landázuri, A., Betterton, E. A., & Sáez, A. E. (2012). A review on the importance of metals and metalloids in atmospheric dust and aerosol from mining operations. *Science of the Total Environment*, *433*, 58-73.

18. Csavina, J., Landázuri, A., Wonaschütz, A., Rine, K., Rheinheimer, P., Barbaris, B., ... & Betterton, E. A. (2011). Metal and metalloid contaminants in atmospheric aerosols from mining operations. *Water, Air, & Soil Pollution*, *221*(1-4), 145-157.

19. Félix, O. I., Csavina, J., Field, J., Rine, K. P., Sáez, A. E., & Betterton, E. A. (2015). Use of lead isotopes to identify sources of metal and metalloid contaminants in atmospheric aerosol from mining operations. *Chemosphere*, *122*, 219-226.

20. Flegal, R. A.,Smith, D. R. (1992). Lead levels in preindustrial humans. *The New England Journal of medicine*, *326*(19), 1293-1294.

21. Gerhardstein, B., Hayden Community Airborne Pb Risk Forecast. Powerpoint Presentation. ADEQ. 2018. Personal communication, community presentation, Jan. 19, 2018.

22. Gould, E. (2009). Childhood lead poisoning: conservative estimates of the social and economic benefits of lead hazard control. *Environmental health perspectives*, *117*(7), 1162-1167

23. Gustavsson, N., Bølviken, B., Smith, D.B., Severson, R.C., 2001. Geochemical Landscapes of the Conterminous United States—New Map Presentations for 22 Elements. Denver CO: U.S. Geological Survey Professional Paper 1648. Lead Map, p. 22.

24. Hilts, S. R. (2003). Effect of smelter emission reductions on children's blood lead levels. *Science of the Total Environment*, *303*(1-2), 51-58.

25. Hogan, K., Marcus, A., Smith, R., & White, P. (1998). Integrated exposure uptake biokinetic model for lead in children: Empirical comparisons with epidemiologic data. *Environmental Health Perspectives,106 Suppl 6*, 1557-67.

26. Hu, H., Shine, J., & Wright, R. O. (2007). The challenge posed to children's health by mixtures of toxic waste: the Tar Creek Superfund Site as a case-study. *Pediatric Clinics of North America*, *54*(1), 155–x. http://doi.org/10.1016/j.pcl.2006.11.009

27. Laidlaw, M. A., Mohmmad, S. M., Gulson, B. L., Taylor, M. P., Kristensen, L. J., & Birch, G. (2017). Estimates of potential childhood lead exposure from contaminated soil using the US EPA IEUBK Model in Sydney, Australia. *Environmental research*, *156*, 781-790.

28. Maddaloni, M., Ballew, M., Diamond, G., Follansbee, M., Gefell, D., Goodrum, P., . . . Zaragoza, L. (2005). Assessing lead risks at non-residential hazardous waste sites. *Human and Ecological Risk Assessment: An International Journal, 11*(5), 967-1003. doi:10.1080/10807030500257838

29. Manjón, I., Ramírez-Andreotta, M., Sáez, A., Root, R., Hild, J., Janes, M., & Alexander-Ozinskas, A. (2020). Ingestion and inhalation of metal(loid)s through preschool gardening: An exposure and risk assessment in legacy mining communities. *Science of the Total Environment, 718*, 134639.

30. Mickle, M. (1998). Structure, use, and validation of the IEUBK model. *Environmental Health Perspectives,106 Suppl 6*, 1531-4.

31. National Environment Protection (Assessment of Site Contamination) Measure (NEPM), 2013b. Blood Lead Model - IEUBK Modelling input parameters - child receptors. Schedule B7, Appendix C. http://www.nepc.gov.au/system/files/resources/93ae0e77-e697-e494-656f-afaaf9fb4277/files/schedule-b7-appendix-c-blood-lead-model-sep10.pdf

32. National Research Council (2005). Chapter 6: Human Health Risk Assessment: Lead Exposure and Uptake - Use of the IEUBK Model." *Superfund and Mining Megasites:*

Lessons from the Coeur d'Alene River Basin. Washington, DC: The National Academies Press. doi: 10.17226/11359.

33. National Research Council (1980). Lead in the human environment. Washington, D.C.: National Academy of Sciences. Report Number PB-82-117136. OSTI Identifier: 5455381; ISBN No. 0309030218.

34. Ramirez-Andreotta, M., Brody, J., Lothrop, N., Loh, M., Beamer, P., & Brown, P. (2016a). Improving environmental health literacy and justice through environmental exposure results communication. *International Journal of Environmental Research and Public Health, 13*(7), 690. doi:10.3390/ijerph13070690

35. Ramirez-Andreotta, M., Brusseau, M., Artiola, J., Maier, R., & Gandolfi, A. (2014). Environmental research translation: Enhancing interactions with communities at contaminated sites. *Science of the Total Environment, 497*, 651-664. doi:10.1016/j.scitotenv.2014.08.021

36. Ramirez-Andreotta, M. D., Lothrop, N., Wilkinson, S. T., Root, R. A., Artiola, J. F., Klimecki, W., & Loh, M. (2016b). Analyzing patterns of community interest at a legacy mining waste site to assess and inform environmental health literacy efforts. *Journal of Environmental Studies and Sciences, 6*(3), 543-555. doi:10.1007/s13412-015-0297-x

37. Rodriguez-Chavez, T., Saez, E., Betterton, E. (2016-2020). Unpublished manuscript in progress.

38. Sorooshian, A., Csavina, J., Shingler, T., Dey, S., Brechtel, F. J., Sáez, A. E., & Betterton, E. A. (2012). Hygroscopic and chemical properties of aerosols collected near a copper smelter: implications for public and environmental health. *Environmental science & technology*, *46*(17), 9473-9480.

39. Spear, T., Svee, W., Vincent, J., & Stanisich, N. (1998). Chemical speciation of lead dust associated with primary lead smelting. *Environmental Health Perspectives,106*(9), 565-571.

40. Thomas, A., Root, R., Lantz, R., Sáez, A., & Chorover, J. (2018). Oxidative Weathering Decreases Bioaccessibility of Toxic Metal(loid)s in PM10 Emissions From Sulfide Mine Tailings. *GeoHealth, 2*(4), 118-138.

41. U.S. Census (2018). *Hayden, Arizona*. Retrieved Feb 18, 2020 from https://factfinder.census.gov/faces/nav/jsf/pages/community_facts.xhtml?src=bkmk

42. U.S. Census (2018). *Winkelman, Arizona*. Retrieved Feb 18, 2020 from https://factfinder.census.gov/faces/nav/jsf/pages/community_facts.xhtml?src=bkmk

43. U.S. EPA. (2006) *Air Quality Criteria for Lead Final Report*. U.S. Environmental Protection Agency, Washington, D.C., EPA/600/R-05/144aF-bF, 2006.

44. U.S. EPA (2015). *Asarco, LLC Settlement*. https://www.epa.gov/enforcement/asarco-llc-settlement

45. U. S. EPA. (1994) *Guidance Manual for the Integrated Exposure Uptake Biokinetic Model for Lead in Children; Chapter 1.* Retrieved March 20, 2020 from https://semspub.epa.gov/work/HQ/174566.pdf.

46. U.S. EPA (2017). *Lead at Superfund Sites: Human Health* Retrieved Jan. 7, 2020 from https://www.epa.gov/superfund/lead-superfund-sites-human-health

47. U. S. EPA. (n.d.) *Lead at Superfund Sites: Software and Users' Manuals for IEUBK Model* Retrieved March 21, 2020 from https://www.epa.gov/superfund/lead-superfund-sites-software-and-usersmanuals#overview

48. U.S. EPA. (2016) *NAAQS*. Retrieved April 1, 2020 from https://www.epa.gov/lead-air-pollution/table-historical-lead-pb-national-ambient-air-quality-standards-naaqs

49. U.S. EPA. (n.d.) *Superfund Alternative Approach*. Retrieved Jan. 7, 2020 from https://www.epa.gov/enforcement/superfund-alternative-approach.

50. U. S. EPA (2001). *User's Guide for the Integrated Exposure Uptake Biokinetic Model for Lead in Children (IEUBK)*. Retrieved Jan 31, 2020 from https://semspub.epa.gov/work/HQ/176289.pdf.

51. von Lindern, I., Spalinger, S., Stifelman, M. L., Stanek, L. W., & Bartrem, C. (2016). Estimating children's soil/dust ingestion rates through retrospective analyses of blood lead biomonitoring from the Bunker Hill Superfund Site in Idaho. *Environmental health perspectives*, *124*(9), 1462-1470.

52. Woolf, A. D., Goldman, R.,&Bellinger, D. C. (2007). Update on the clinical management of childhood lead poisoning. *Pediatric Clinics*, *54*(2), 271-294.

53. Zaragoza, L., & Hogan, K. (1998). The integrated exposure uptake biokinetic model for lead in children: Independent validation and verification. *Environmental Health Perspectives, 106*, 1551-1556.

54. Zheng, J., Huynh, T., Gasparon, M., Ng, J., & Noller, B. (2013). Human health risk assessment of lead from mining activities at semi-arid locations in the context of total lead exposure. *Environmental Science and Pollution Research*, *20*(12), 8404-8416.

55. Zota A.R., Schaider L.A., Ettinger A.S., Wright R.O., Shine J.P., Spengler J.D.. Metal sources and exposures in the homes of young children living near a mining-impacted

Superfund site. *Journal of exposure science & environmental epidemiology*. 2011;21(5):495-505. doi:10.1038/jes.2011.21.

56. Zota, A. R., Willis, R., Jim, R., Norris, G. A., Shine, J. P., Duvall, R. M., . . . Spengler, J. D. (2009). Impact of mine waste on airborne respirable particulates in northeastern Oklahoma, United States. *Journal of the Air & Waste Management Association, 59*(11), 1347-1357. doi:10.3155/1047-3289.59.11.1347

APPENDIX B: An Evaluation of Risk Communication in a Rural Mining Community

Authors: Dominika Heusinkveld[1] and Mónica Ramírez-Andreotta[1,2]

[1]Department of Environmental Science, University of Arizona; [2]Mel and Enid Zuckerman College of Public Health's Division of Community, Environment & Policy, University of Arizona

Prepared for: *Journal of Science Communication*

***Corresponding Author:**
Mónica Ramírez-Andreotta, M.P.A, Ph.D.
1177 E Fourth Street, Rm. 429, Tucson, AZ 85721
Phone: 520-621-0091; Fax: 520-621-1647
Email: mdramire@email.arizona.edu

Introduction

Mining communities are particularly vulnerable to environmental health hazards and are at risk for environmental justice issues. Rural communities are beholden to large employers such as mining companies for economic security, and members may be reluctant to voice concerns (ADHS, 2002). In addition, communities may be suspicious of regulatory agencies (Ramirez-Andreotta, 2016b; Muro et al., 2012). However, past research has shown that communities in contaminated areas are eager for information, particularly on how to reduce their risks of exposure (Ramirez-Andreotta, 2016b; Brody et al., 2007; Fischer, 1991).

Risk communication in contaminated communities faces a number of challenges. The traditional approach used by agencies has been a one-way communication model in which an agency relates information on risks to the community without feedback from residents (Muro et al., 2012). In this type of communication, the framing of risk is entirely done by the agencies (Wiseen & Wester-Herber, 2007). The public is not asked what risks they are concerned about; they are simply told what risks they *should* worry about.

This approach results in conflict, because the public tends to think of risk in terms of its consequences, while risk managers tend to think of risk in terms of probabilities (Wiseen & Wester-Herber, 2007). As Slovic (1997) states, "Risk assessment is inherently subjective and represents a blending of science and judgement with important psychological, social, cultural, and political factors" (p. 00). This conflict of values may result in mistrust or perceived apathy in communities affected by environmental contamination. Such conflicts may manifest as lack of attendance at community meetings, hostility when speaking with risk managers, and risk prioritization that does not reflect true health consequences in the community. As Slovic states in his 1987 study:

> *[The public's] basic conceptualization of risk is much richer than that of the experts and reflects legitimate concerns that are typically omitted from expert risk assessments. As a result, risk communication and risk management efforts are destined to fail unless they are structured as a two-way process. (p. 285)*

Risk communication is further complicated by the amount of uncertainty involved in estimating risks. The risk of an exposure to a toxin, for example, must take into account the dose of the toxin, the likelihood a person will come into contact with it, how often the exposure will happen and over what period of time, how readily absorbed the toxin is, and a number of other biological factors for which a risk manager is unlikely to have data. While estimates exist for some of these data points, each exposure site and population are different, and a lot of educated guessing takes place in the typical risk assessment. This process is difficult to convey to a lay audience. It also requires risk managers to prioritize certain risks over others and make value judgments. As Slovic (1997) states, "Defining risk is thus an exercise in power" (p. 54).

While experts tend to rank risks according to probability of adverse outcome, some risks are inherently perceived to be worse than others by members of the public, regardless of their probability. Numerous studies over the years have documented that risks which are catastrophic, not under individual control, involuntary, man-made, new or unfamiliar, and affect future generations are seen as worse (more alarming) than risks with the opposite qualities (Ropeik & Slovic, 2003). Perhaps the most inflating quality of a risk is its dread factor—the amount of fear it invokes. For example, most people do not worry excessively about dying in a car accident, but they do worry about dying in an airplane crash—despite the fact that the former is much more likely than the latter (Slovic, 1987, 1997). Factors such as dread, lack of control, unfairness of exposure, and a perceived "morality" of a risk also are associated more with public outrage and anger (Sandman, 1987). Thus, public agencies whose job it is to communicate risk to the public must take a number of complex factors into account when structuring their messages.

The question of how best to communicate environmental science issues and risk to the public has been ongoing for many years. The National Institute of Environmental Health Sciences has worked since the 1990s on a translational research program, which has expanded to Superfund communities (Ramirez-Andreotta, 2014). Community engagement has been part of the EPA's Superfund program as well. Various approaches, including citizen science, informal science education, community-based participatory research, popular epidemiology, and others have been studied in the field (Ramirez-Andreotta, 2014). Studies in health and risk communication in particular have suggested that communities should participate in the risk analysis and management processes (Ramirez-Andreotta, 2014; Bickerstaff, 2004; Ropeik & Slovic, 2003). The public also wants researchers to present them with possible actions to reduce their risks (Brody et al., 2007). Fischer et al. (1991) showed that people "are most likely to act on risks where they feel efficacious and responsible and have the information needed to take effective action" (p. 00). Thus, agencies can encourage productive risk management by providing communities with options for reducing their risks.

Keeney and Winterfeldt (1986) suggested a set of objectives to aid in designing risk communication to communities. These are as follows (p. 421):

1. To better educate the public about risks, risk analysis, and risk management
2. To better inform the public about specific risks and the actions taken to alleviate them
3. To encourage personal risk reduction measures
4. To improve the understanding of public values and concerns
5. To increase mutual trust and credibility

6. To resolve conflicts and controversy

These objectives can be used to help a risk-management agency structure its risk communications strategy.

Once a risk communication is taking place, it is important to gather feedback to determine how effective the communication strategy is. Weinstein and Sandman (1992) proposed seven criteria that can be used to evaluate communication efforts to communities regarding risk. They are as follows (p. 104):

1. Comprehension: Does the audience understand the content?
2. Agreement: Does the audience agree with the recommendation/interpretation in the message?
3. Dose-response consistency: Do people facing a higher dose of a hazard perceive the risk as greater or show a greater readiness to take action than those exposed to a lower dose of this hazard?
4. Hazard response consistency: Do people facing a higher risk perceive this and show a greater readiness to take action?
5. Uniformity: Do people exposed to the same level of risk have the same or similar response?
6. Audience evaluation: Does the audience find the message helpful, accurate, and clear?
7. Communication failures: Are the failures that occur serious?

These objectives and criteria may serve as a useful guide for structuring and communicating the results of risk analyses. Questions remain, however, about the best process for conveying information to a community. In the past, regulatory agencies and scientists have relied on community meetings and slideshow presentations, as well as local media, to communicate the science behind risk estimates. These tend to be one-way communication efforts (Muro, et al. 2012). In recent years, options have expanded to include phone apps, videos, story maps, infographics, podcasts, and other multimedia. Some experts contend that in-person interaction is the best way to communicate with a community about risk, because it fosters relationship-building and trust and has more potential for two-way communication (Galvez et al. 2007).

Study Description

The towns of Hayden-Winkelman, Arizona, are located about 70 miles northeast of Tucson and neighbor a copper mining and smelting site that has been operating for many decades. The community is a Superfund Alternative Site, according to the U.S. EPA.(U.S. EPA, *ASARCO Hayden Plant*, n.d.). Over the past two decades, various state, federal, and local agencies have evaluated the extent of environmental contamination on the site, which has resulted from mining and smelting activities. Numerous site evaluations have shown elevated lead levels in the air, soil, and dust (ADHS, 2018 & 2002; ATSDR, 2017) in addition to other environmental contaminants. These were reviewed and discussed at length in Appendix A.

One of the state agencies involved with remediation and evaluation in the community has been the Arizona Department of Environmental Quality (ADEQ). Over the years, it has used traditional methods (community presentations, handouts) to communicate exposure risks. In 2016, the ADEQ developed an air lead risk forecast program and accompanying electronic dissemination tools to share the predicted and forecasted risk of lead exposure with the Hayden-Winkelman community.

The current study attempts to determine how best to communicate risk levels from lead to this community and whether the ADEQ's air lead risk forecast is an effective way to accomplish that communication. This thesis research project evaluates the ADEQ's risk communication efforts based on recommendations found in the risk communication literature.

Methods

In order to critique the ADEQ's risk communication, the forecast methodology as well as the communication efforts are reviewed below.

ADEQ Air Lead Forecast Methodology

The ADEQ began providing an airborne lead risk forecast in 2016 to the Hayden community (ADEQ, *Air Forecasting,* n.d.). The goal of the forecast is to communicate to Hayden-Winkelman residents what days they may expect a higher exposure to airborne lead based on the weather forecast—somewhat analogous to an "air quality forecast" provided by news media in many communities. The forecast is predictive and is validated with air lead data collected by ADEQ at two sites in the community. The samples are collected, assayed for lead concentrations in air, and then used retrospectively to refine the ADEQ's forecast model (ADEQ, *Air Forecasting,* n.d.).

The forecast is based chiefly on the direction and speed of wind expected for a given day in the area. Because the residential area in Hayden is located just west of the smelter, ADEQ has found that wind directions out of the east are linked to higher air lead risk. Table 1 shows the wind speeds registered at the two ADEQ sensors used in this risk evaluation and the air lead risk values associated with the given wind speeds. These sensors were located at the Hillcrest site and the Globe Highway site and can be seen on the satellite map in Figure 1. In general, maximum (mean) wind speeds below about 19 mph (8.5 mph) were associated with a low risk forecast. Maximum (mean) wind speeds over about 24 mph (12 mph) were associated with a high risk forecast. Rainy days resulted in low risk forecasts (ADEQ, 2018, slide 33) due to the decrease in dust levels associated with rain.

ADEQ's three air lead risk categories—green, yellow, and red—correspond to low, moderate, and high risk, respectively (see Figure 2). These particular exposure levels were calculated by ADEQ as follows (ADEQ, 2018, slide 19):

- The "low" risk level is set at the current lead NAAQS rolling three-month average of 0.15 ug m^{-3} (U.S. EPA, 2016).
- The" high" risk level was calculated based on the average daily dietary intake of lead for an adult (age 25-30) male (4.17 ug/day), obtained from the FDA Total Diet Study 1990-1991 figures from Bolger, et al., Table 1, p.36 (1996).
    - The average breath volume for an adult male (500 mL) and the average respiratory rate for an adult male (20 breaths per minute) led to a calculated exposure of 14.4 m^3 air per day.
    - Further calculation revealed that an ambient air lead concentration of 0.29 ug m^{-3} is needed to reach 4.17 ug per day; the high-risk level was therefore set at >0.30 ug m^{-3}.
- The "moderate" risk level is set between the high and low values.

ADEQ's Communication Strategies

Community members can sign up on the ADEQ website to receive the day's forecast via email or text. They can also download the Air Arizona app on their phone. The forecast tells the subscriber what the air lead risk category is for that particular day (Figure 3). Subscribers can click on the link to the website listed in the email or text for a more detailed forecast for the week posted on the ADEQ website (Figure 4). Of note, the air forecast located on the website and distributed in the email and text messages does not contain information on mitigation actions.

In the app, information can be found about mitigation actions. Under the "About Lead" section when clicking on the "Lead forecast levels" button, there is an explanation of the forecast as well as the risk-reduction action recommendations for the low, moderate, and high forecast categories (see Figures 5 and 6).

Results

According to data collected by ADEQ on community engagement, the following data can be reported regarding the Hayden-Winkelman community's utilization of the ADEQ's Air Lead Risk Forecast (James, B.; personal communication, 2020):

1. On December 9, 2017, ADEQ held a community meeting to gather public input on how to disseminate the lead air forecasts to the community. There were seven community attendees.
2. Since 2017, 482 unique web page views of the ADEQ's Hayden Air lead Risk Forecast web page have been recorded
3. As of March 31, 2020, 613 subscribers had signed up for the email/text air lead risk forecast.

4. Between July 1, 2019 and March 31, 2020, there have been a total of 1,198 downloads and app opens (referred to as "first open conversions") of the Air Arizona mobile app. This app includes forecasts and air quality data for other areas of Arizona in addition to the Hayden area. ADEQ cannot differentiate between Hayden-Winkelman users and app users from other communities.

For reference, the most recent census data from the Hayden-Winkelman communities report a population of 662 in Hayden and 352 in Winkelman (U.S. Census, 2018) for a total of 1,104 in the community.

Discussion

The statistics reported by the ADEQ indicate that email/text subscription has the most exposure in the community, followed by the ADEQ's forecast website. The Air Arizona app may also be successful, but since Hayden subscribers are not differentiated, this form of risk communication cannot be evaluated. Very few community members attended the face-to-face community presentation. The lack of community engagement with risk managers may be due to a number of factors: lack of trust, lack of concern about their exposure, fear and denial, economic concerns, and other factors. In communities such as Hayden-Winkelman, where the sole employer is also the source of the hazard, cognitive conflicts can arise as people try to balance their need for paying jobs with their desire for health. These conflicts can go beyond simple worry over repercussions from an employer. Bickerstaff (2004) states that some industrial communities have come to equate "pollution and health damage with economic vitality" (p. 831). Thus, in communities that have a long history of pollution associated with employment opportunities, pollution can become a symbol of local culture and identity.

Recent developments in the Hayden-Winkelman community, including the shutdown of the smelter in October 2019 due to a labor dispute (Presnell, 2019), make community engagement and communication all the more challenging. Below is a potential strategy for improving risk communication in the community.

Heusinkveld et al. (2020) found that the ADEQ's air lead risk forecast is unlikely to have any mitigating effects on lead exposure in the community's children, because the majority of their lead exposure is through indoor dust. Nevertheless, because lead exposure is cumulative and particularly harmful in children, it would be wise to reduce all possible sources of lead exposure.

Including information on hazard mitigation in ADEQ's email and web-based forecasts, much as ADEQ does in the Air Arizona app, is recommended, particularly since it seems that email notifications have a high number of subscribers. In children the dust, food, and water ingestion pathway is the dominant exposure pathway for lead. In adults, ingestion of soil and dust is about one-fifth that of children, and lead gastrointestinal absorption is also low (Bowers, 1994), making the inhalation pathway proportionately more important. While the relationship between BLL and air lead concentration is not linear, studies have indicated that 1 ug of lead per m^3 of air raises BLLs in adults by approximately 1 ug dL^{-1} for air lead concentrations between 1 and 5 ug dL^{-1}(Mahaffey, 1977). Mahaffey (1977) estimates that adults absorb about 40% of inhaled lead, while Bowers et al. estimate 32% (1994). Whatever the actual risks are, community members can benefit from hazard mitigation measures, such as wet mopping, avoiding outdoor activity, and closing windows on high risk days. In addition, vacuuming frequently with HEPA filter vacuums, wiping down windowsills and surfaces frequently, and frequently changing HVAC air filters should be recommended for this community. Proposing risk mitigation actions would allow community members to take some control over their exposures and would help mitigate the “lack of individual control” factor in the risk (Ropeik & Slovic, 2003), likely resulting in a reduced feeling of dread.

Keeney and Winterfeldt’s (1986) objectives are most useful at the start of a risk communication project and can be used while designing the risk communication to ensure that the necessary objectives are met. For an existing risk communication such as this one, evaluating how well the ADEQ forecast meets the seven criteria listed in Weinstein and Sandman (1993) may result in more effective risk communication for adults in the Hayden-Winkelman communities. A simple way to do this would be through short surveys attached to the emails or within the app sent out on days when the risk forecast is “moderate” or “high.” Subscribers could be given a link to answer a particular question—for instance, “Will you do anything differently today now that you are aware of the forecast?” or “Do you feel this information is clear to you?” Single questions take much less time to answer than conventional surveys. Over time, the ADEQ could collect enough information from its audience to determine whether the air lead risk forecast is helpful to the community. Survey questions within the app could also help determine how many subscribers are from the Hayden-Winkelman community. This information would steer future improvements of ADEQ’s risk communication. Table 2 contains the seven criteria and some suggested questions that could be used to evaluate performance, as well as some notes on the criteria.

It would also be helpful to get feedback from members of the community who do not subscribe. Davis, Ramirez-Andreotta, and Buxner (2020) found that of 120 participants in citizen science projects in rural Arizona, 18% reported no computer or internet access. One of the communities in this study is Hayden-Winkelman. Surveying nonsubscribers could elucidate the reasons for not participating in the risk communication. This would likely need to be done at public community events where staff could ask community members whether they subscribe and give a brief survey to those who do not. This information gathering would be a challenge because in the past, community members have not turned out for ADEQ-hosted meetings. One suggestion is for agency personnel to attend a community event and staff a table where some free merchandise would be given away in return for answering some survey questions. Another strategy would be to capitalize on existing community events. For example, high school sports events are an integral component of the town's culture and spirit. Integrating the information into popular community events can help to raise awareness of the risk for athletes and families who attend outdoor events.

Conclusion

The subtleties of risk analysis add a layer of complexity to communicating exposure risks. A number of estimates and guesses are made in any risk assessment. These "educated guesses" can be difficult to explain to a lay public, and inherently involve some judgment calls. The differing priorities of risk managers and communities when measuring risk add yet another complication. Strategies for communicating those subtleties are still being evaluated in the literature.

A challenge in this community has been its small size and its lack of engagement in past attempts at risk communication. Lack of engagement may be due to a number of factors, and investigating the effectiveness of this risk communication can help elucidate those factors. Keeney and Winterfeldt's (1986) objectives can be used during the design phase of a risk communication to ensure that the communication meets the necessary objectives for success.

Where a risk communication message already exists, as in the case of the ADEQ's air lead risk forecast, Weinstein and Sandman's criteria for evaluating risk messages can be helpful in testing the effectiveness of the ADEQ's communication strategy.

An important factor to keep in mind is that communities need to be involved in two-way communication with the risk managers at all points during the risk assessment and communication. This engagement ensures that a relationship is fostered and the questions and anxieties of the community are answered. Lay people have different priorities than risk managers, but these differences must be brought out into the open. Once two-way communication is established, risk managers will find it easier to communicate with the public, even if they do not always agree.

Acknowledgments

I would like to thank ADEQ staff, particularly Byron James, for providing the data used in this study.

APPENDIX B FIGURES AND TABLES

Table 1: Wind speeds in miles per hour and their associated risk levels at the Hillcrest and Globe Highway sensors in Hayden.

	Low Risk	Moderate Risk	High Risk
Hillcrest mean	8.4	9.4	12
Hillcrest max	18.7	19.2	23.8
Globe Highway mean	9.1	9.1	11.2
Globe Highway max	19.0	21.7	24.6

Figure 1: Map of site showing location of ASARCO smelter, Hayden, and the Globe and Hillcrest air monitors. (ADEQ Powerpoint, Slide 3)

Figure 2: ADEQ's lead risk forecast categories.

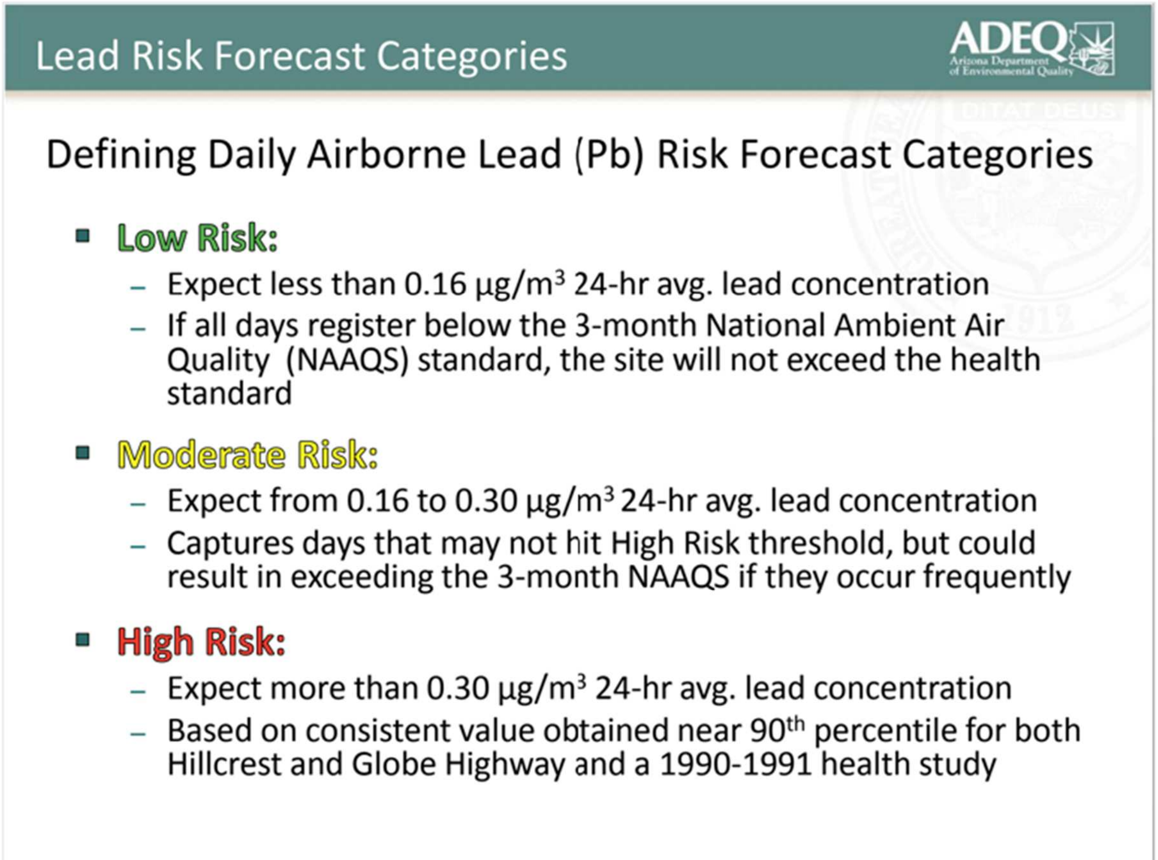


Figure 3: Screenshot of the ADEQ's daily air lead forecast as it appears in email.

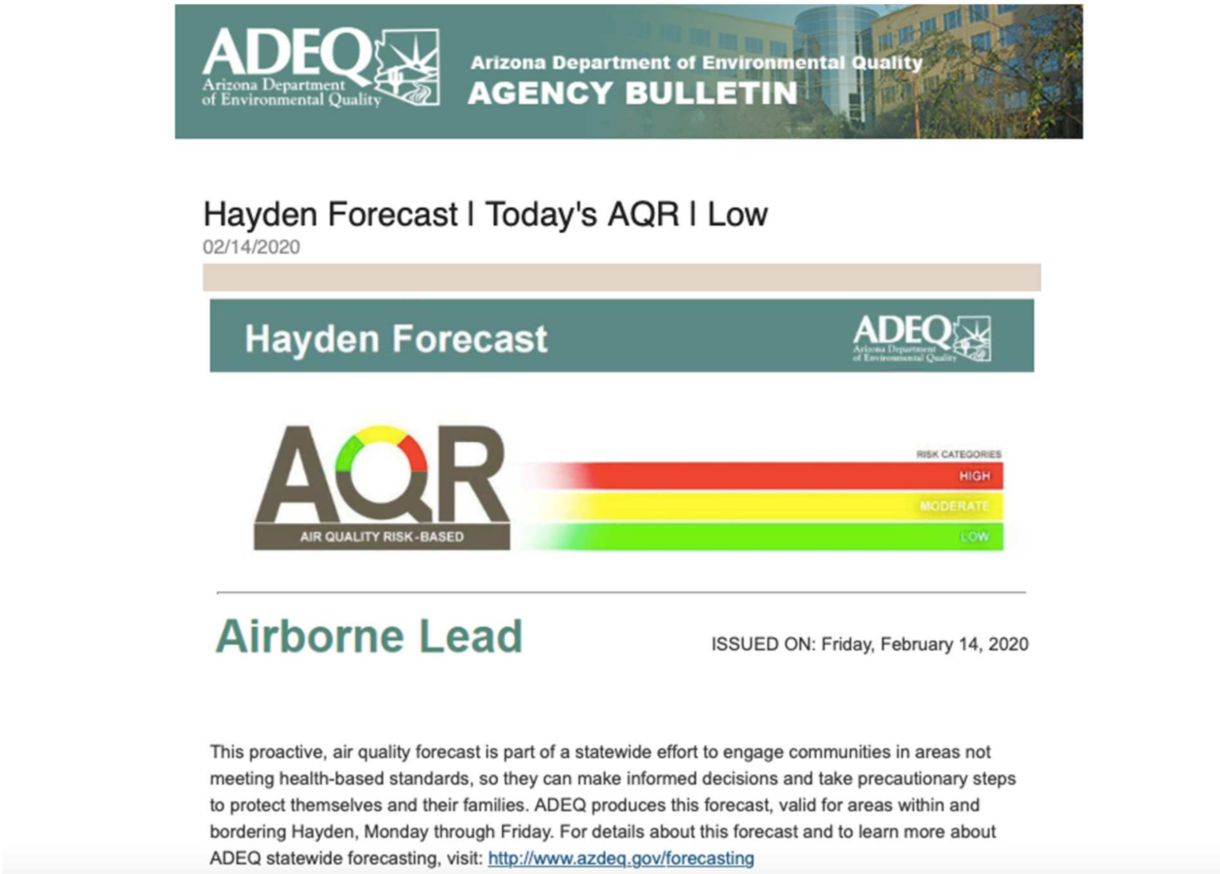


Figure 4: Screenshot of the ADEQ's detailed forecast as it appears on their website.

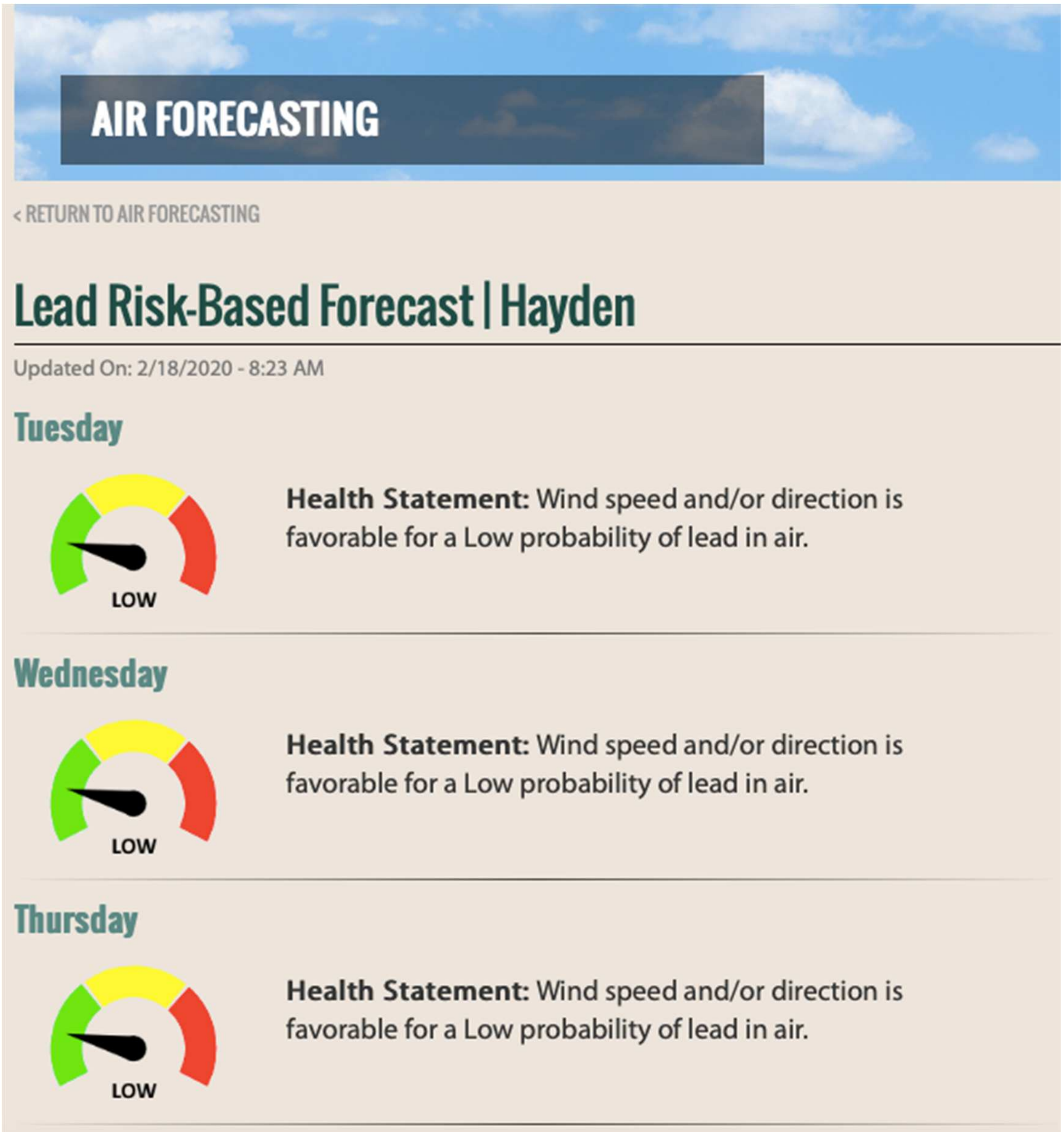
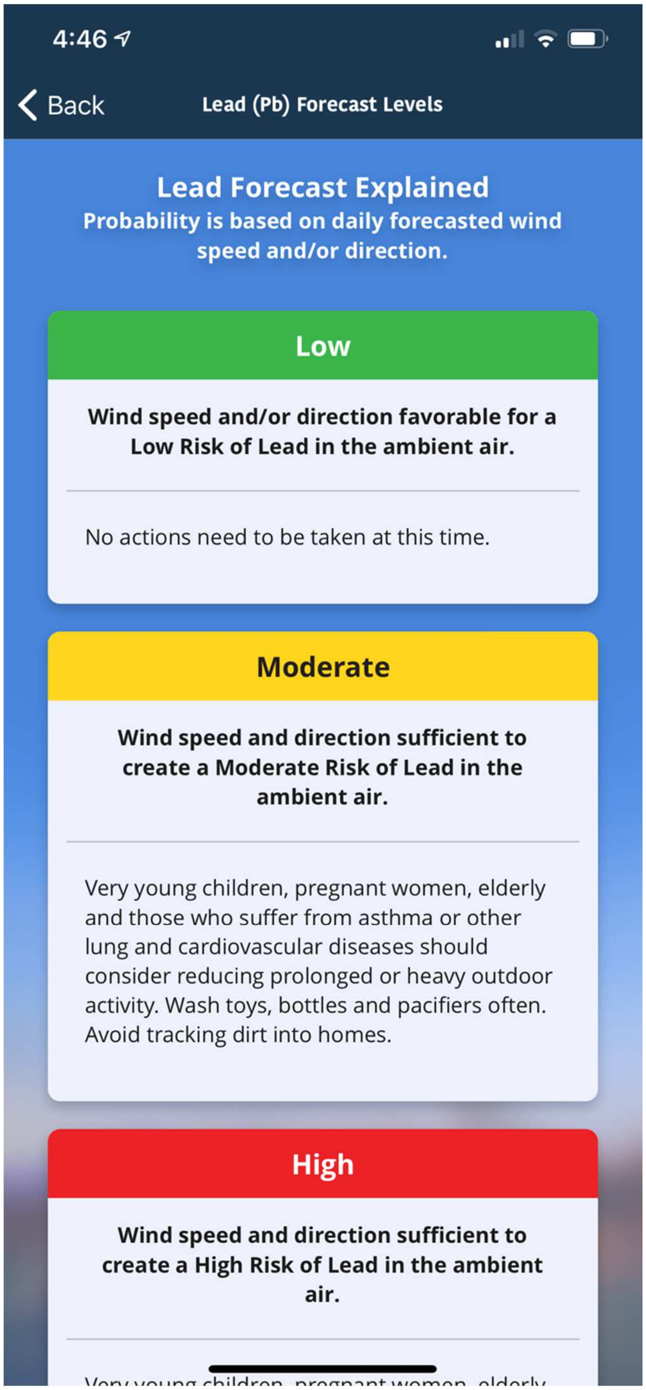
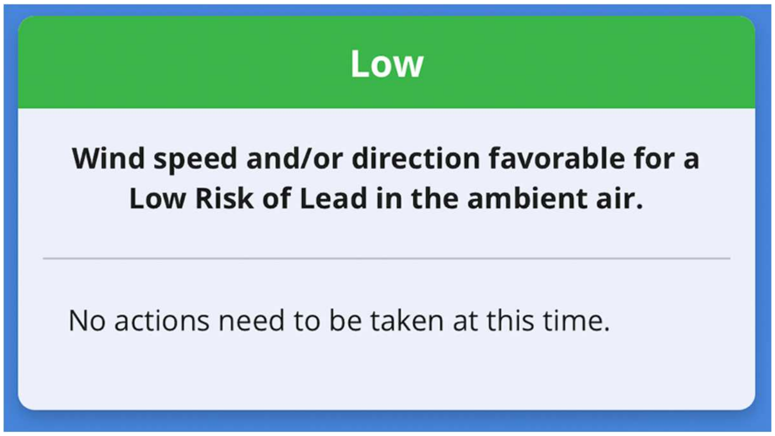


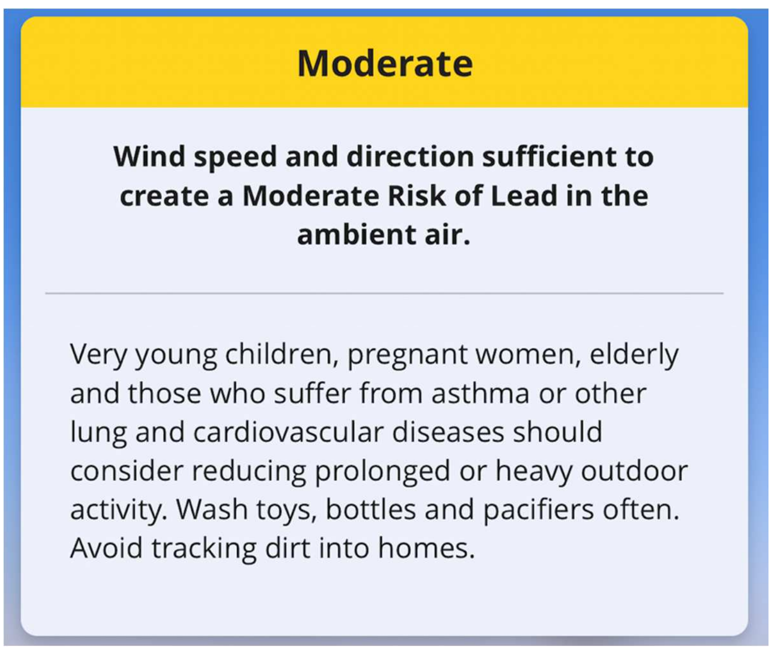
Figure 5: Explanation of the air lead forecast risk levels on the ADEQ's Arizona Air app and the recommended risk modification actions. (A) is Low, (B) is Moderate, and (C) is High.



A


Low
Wind speed and/or direction favorable for a Low Risk of Lead in the ambient air.
No actions need to be taken at this time.

B


Moderate
Wind speed and direction sufficient to create a Moderate Risk of Lead in the ambient air.
Very young children, pregnant women, elderly and those who suffer from asthma or other lung and cardiovascular diseases should consider reducing prolonged or heavy outdoor activity. Wash toys, bottles and pacifiers often. Avoid tracking dirt into homes.

C

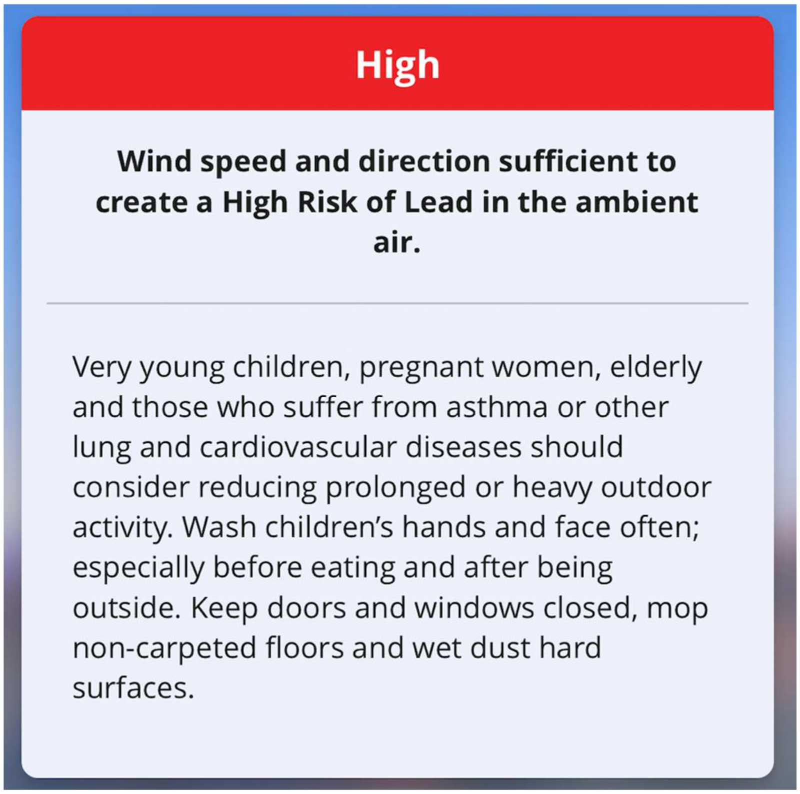

High
Wind speed and direction sufficient to create a High Risk of Lead in the ambient air.
Very young children, pregnant women, elderly and those who suffer from asthma or other lung and cardiovascular diseases should consider reducing prolonged or heavy outdoor activity. Wash children’s hands and face often; especially before eating and after being outside. Keep doors and windows closed, mop non-carpeted floors and wet dust hard surfaces.

Table 2: Weinstein and Sandman's (1993) criteria for evaluating risk messages with suggested questions and notes.

Evaluation Criterion	Suggested Question	Notes
Comprehension: Does the audience understand the content?	What is the purpose of the air lead risk forecast?	What meaning did the audience take from the message? This may be a "knowledge" question or a "meaning" question.
Agreement: Does the audience agree with the recommendation or interpretation in the message?	Do you think high risk forecasts mean you are at more risk from lead? On a scale of 1-5, how much do you trust the state and federal agencies to protect your health?	Consider the goal: are you trying to persuade or inform?
Dose-response consistency: Do people facing a higher dose of a hazard perceive the risk as greater or show a greater readiness to take action than those exposed to a lower dose of this hazard?	Do you do anything differently on Moderate risk days? High risk days?	Applies to different exposures to a single hazard. Small increases in risk should result in small differences in response.
Hazard response consistency: Do people facing a higher risk perceive this and show a greater readiness to take action?	On a scale of 1-5, how worried are you about inhaled lead in your town? How would you compare your worry to worry about (Hazard X)?	Applies to comparisons across hazards. Outrage/dread along with lack of trust can affect these responses significantly.
Uniformity: Do people exposed to the same level of risk have the same or similar response?	What does a "high" risk forecast mean to you?	Does everyone interpret this communication the same way?
Audience evaluation: Does the audience find the message helpful, accurate, and clear?	On a scale of 1-5, how helpful was this message? On a scale of 1-5, how clear was this message?	The audience isn't always right! Sometimes people like communications that aren't particularly effective when evaluated by other means.
Communication failures: What happens when the communication fails? Is there harm?	Do people overreact or underreact to the forecast? What are the consequences of this reaction?	Ask what harm can occur from the communication failures you have diagnosed.

APPENDIX B REFERENCES

1. Arizona Department of Environmental Quality. (2019) *Air Forecasting.* Retrieved April 3, 2020 from https://www.azdeq.gov/forecasting

2. Arizona Department of Environmental Quality. (2019) *Air Arizona Mobile App.* Retrieved April 3, 2020 from https://azdeq.gov/AirAZ

3. Arizona Department of Environmental Quality. (2018) *Hayden Community Airborne Pb Risk Forecast*. Powerpoint Presentation to Hayden Community.

4. Arizona Department of Environmental Quality. (n.d.) *Lead Risk-Based Forecast, Hayden.* Retrieved March 30, 2020 from http://azdeq.gov/node/5131

5. Arizona Department of Health Services (May 2018). *Arizona Department of Health Services Health Consultation: Evaluation of Community Exposure to Lead and Sulfur Dioxide in Air. Hayden and Winkelman Communities.* https://www.atsdr.cdc.gov/HAC/pha/haydenWinkelman/ADHS_Hayden_Air_HC-508.pdf

6. Arizona Department of Health Services (2002). *Public Health Assessment, ASARCO Hayden Smelter Site; Hayden, Arizona.* https://www.azdhs.gov/documents/preparedness/epidemiology-disease-control/environmental-toxicology/asarco-hayden.pdf

7. Agency for Toxic Substances and Disease Registry Exposure Investigation (March 2017). *Biological Testing for Exposure to Lead and Arsenic near Asarco Hayden Smelter Site; Hayden and Winkelman, Arizona.* https://www.atsdr.cdc.gov/HAC/pha/AsarcoHaydenSmelterSite/AsarcoHaydenSmelterSite_HC_EI_03272017_508.pdf

8. Bickerstaff, K. (2004). Risk perception research: socio-cultural perspectives on the public experience of air pollution. *Environment international*, *30*(6), 827-840.

9. Bolger, P., Yess, N., Gunderson, E., Troxell, T., & Carrington, C. (1996). Identification and reduction of sources of dietary lead in the United States. *Food Additives & Contaminants, 13*(1), 53-60.

10. Bowers, T. S., Beck, B. D., & Karam, H. S. (1994). Assessing the relationship between environmental lead concentrations and adult blood lead levels. *Risk Analysis*, *14*(2), 183-189.

11. Brody, J. G., Morello-Frosch, R., Brown, P., Rudel, R. A., Altman, R. G., Frye, M., ... & Seryak, L. M. (2007). Improving Disclosure and Consent: “Is It Safe?”: New Ethics for Reporting

Personal Exposures to Environmental Chemicals. *American Journal of Public Health*, *97*(9), 1547-1554

12. Davis, L.F., Ramírez-Andreotta, M.D. and Buxner, S.R. (2020). Engaging Diverse Citizen Scientists for Environmental Health: Recommendations from Participants and *Promotoras*. *Citizen Science: Theory and Practice*, 5(1), p.7. DOI: http://doi.org/10.5334/cstp.253

13. Galvez, M. P., Peters, R., Graber, N., & Forman, J. (2007). Effective risk communication in children's environmental health: lessons learned from 9/11. *Pediatric Clinics of North America*, *54*(1), 33-46.

14. Heath, R. L., Seshadri, S., & Lee, J. (1998). Risk communication: A two-community analysis of proximity, dread, trust, involvement, uncertainty, openness/accessibility, and knowledge on support/opposition toward chemical companies. *Journal of Public Relations Research*, *10*(1), 35-56.

15. James, B. ADEQ Community Liaison. Personal Communication, April 1, 2020.

16. Keeney, R. L., & Winterfeldt, D. (1986). Improving risk communication. *Risk analysis*, *6*(4), 417-424.

17. Mahaffey, K. R. (1977). Quantities of lead producing health effects in humans: sources and bioavailability. *Environmental health perspectives*, *19*, 285-295.

18. Muro, M., Hrudey, S. E., Jude, S., Heath, L., & Pollard, S. (2012). Making it real: what risk managers should know about community engagement. *Journal of Environmental Assessment Policy and Management*, *14*(02), 1250010.

19. Peters, R. G., Covello, V. T., & McCallum, D. B. (1997). The determinants of trust and credibility in environmental risk communication: An empirical study. *Risk analysis*, *17*(1), 43-54.

20. Presnell, K. “Workers vote to strike against Tucson-based ASARCO over ‘insulting’ contract offer”. Oct. 11, 2019. Arizona Daily Star. https://tucson.com/news/local/workers-vote-to-strike-against-tucson-based-asarco-over-insulting/article_38ace9de-ecac-11e9-89b6-77c2d4dc779e.html

21. Ramirez-Andreotta, M., Brusseau, M., Artiola, J., Maier, R., & Gandolfi, A. (2014). Environmental research translation: Enhancing interactions with communities at contaminated sites. *Science of the Total Environment, 497*, 651-664. doi:10.1016/j.scitotenv.2014.08.021

22. Ramirez-Andreotta, M. D., Lothrop, N., Wilkinson, S. T., Root, R. A., Artiola, J. F., Klimecki, W., & Loh, M. (2016b). Analyzing patterns of community interest at a legacy mining waste site to assess and inform environmental health literacy efforts. *Journal of Environmental Studies and Sciences, 6*(3), 543-555. doi:10.1007/s13412-015-0297-x

23. Ropeik, D., & Slovic, P. (2003). Risk communication: A neglected tool in protecting public health. *Risk in perspective*, *11*(2), 1-4.

24. Sandman, P. M. (1987). Risk communication: facing public outrage. *EPA J.*, *13*, 21.

25. Slovic, P. (1987). Perception of risk. *Science*, *236*(4799), 280-285.

26. Slovic, P. (1997). Public perception of risk. *Journal of environmental health*, *59*(9), 22-25.

57. U.S. Census (2018). *Hayden, Arizona*. Retrieved Feb 18, 2020 from https://factfinder.census.gov/faces/nav/jsf/pages/community_facts.xhtml?src=bkmk

58. U.S. Census (2018). *Winkelman, Arizona*. Retrieved Feb 18, 2020 from https://factfinder.census.gov/faces/nav/jsf/pages/community_facts.xhtml?src=bkmk

59. U.S. EPA. (n.d.) ASARCO Hayden Plant, Hayden, AZ Retrieved April 3, 2020 from https://cumulis.epa.gov/supercpad/SiteProfiles/index.cfm?fuseaction=second.Cleanup&id=0900497#bkground

60. U.S. EPA. (2016) *NAAQS*. Retrieved April 1, 2020 from https://www.epa.gov/lead-air-pollution/table-historical-lead-pb-national-ambient-air-quality-standards-naaqs

27. Weinstein, N. D., & Sandman, P. M. (1993). Some criteria for evaluating risk messages. *Risk Analysis*, *13*(1), 103-114.

28. Wiséen, T., & Wester-Herber, M. (2007). Dirty soil and clean consciences: Examining communication of contaminated soil. *Water, Air, and Soil Pollution*, *181*(1-4), 173-182.