FRAMEWORK FOR COLLECTING SITE-SPECIFIC SAMPLING AND SURVEY DATA TO SUPPORT ANALYSIS OF HEALTH IMPACTS FROM LAND-BASED POLLUTION IN LMICS

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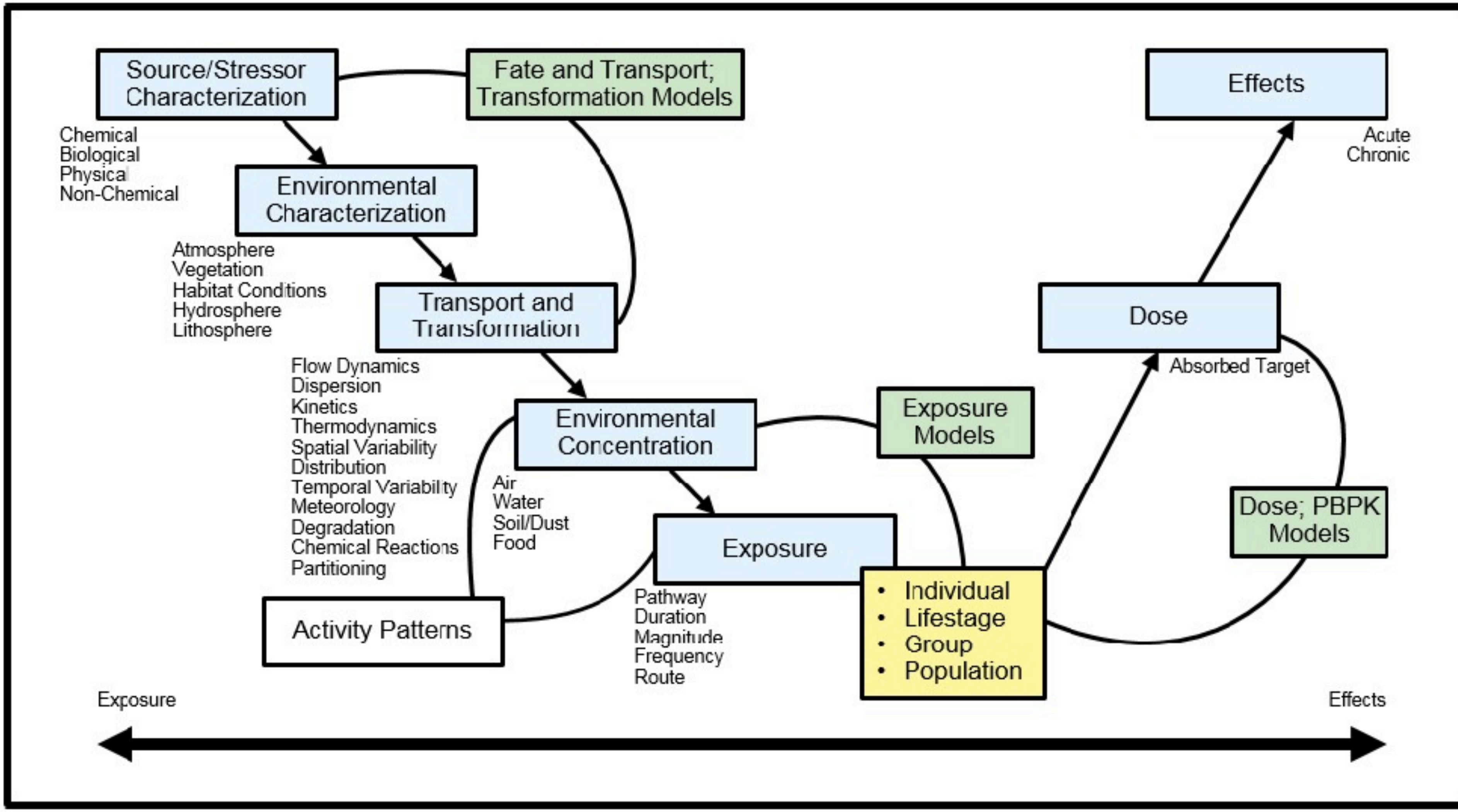
November 18, 2021



Note: PBPK = physiologically based pharmacokinetic
Adapted from NRC (1983); NRC (1997)

International Journal of
Environmental Research and Public Health

MDPI

Article

A Systematic Framework for Collecting Site-Specific Sampling and Survey Data to Support Analyses of Health Impacts from Land-Based Pollution in Low- and Middle-Income Countries

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Abstract: The rise of small-scale and localized economic activities in low- and middle-income countries (LMICs) has led to increased exposures to contaminants associated with these processes and the potential for resulting adverse health effects in exposed communities. Risk assessment is the process of building models to predict the probability of adverse outcomes based on concentration-response functions and exposure scenarios for individual contaminants, while epidemiology uses statistical methods to explore associations between potential exposures and observed health outcomes. Neither approach by itself is practical or sufficient for evaluating the magnitude of exposures and health impacts associated with land-based pollution in LMICs. Here we propose a more pragmatic framework for designing representative studies, including uniform sampling guidelines and household surveys, that draws from both methodologies to better support community health impact analyses associated with land-based pollution sources in LMICs. Our primary goal is to explicitly link environmental contamination from land-based pollution associated with specific localized economic activities to community exposures and health outcomes at the household level. The proposed framework was applied to the following three types of industries that are now widespread in many LMICs: artisanal scale gold mining (ASGM), used lead-acid battery recycling (ULAB), and small tanning facilities. For each activity, we develop a generalized conceptual site model (CSM) that describes qualitative linkages from chemical releases or discharges, environmental fate and transport mechanisms, exposure pathways and routes, populations at risk, and health outcomes. This upfront information, which is often overlooked, is essential for delineating the contaminant zone of influence in a community and identifying relevant households for study. We also recommend cost-effective methods for use in LMICs related to environmental sampling, biological monitoring, survey questionnaires, and health outcome measurements at contaminated and unexposed reference sites. Future study designs based on this framework will facilitate consistent, comparable, and standardized community exposure, risk, and health impact assessments for land-based pollution in LMICs. The results of these studies can also support economic burden analyses and risk management decision-making around site cleanup, risk mitigation, and public health education.

Keywords: risk assessment; burden of disease; low- and middle-income countries; biomonitoring

check for updates

Citation: von Stackelberg, K.; Williams, P.R.D.; Sánchez-Triana, E. A Systematic Framework for Collecting Site-Specific Sampling and Survey Data to Support Analyses of Health Impacts from Land-Based Pollution in Low- and Middle-Income Countries. *Int. J. Environ. Res. Public Health* **2021**, *18*, 4676. https://doi.org/10.3390/ijerph18094676

Academic Editor: Paul B. Tchounwou

Received: 25 March 2021
Accepted: 23 April 2021
Published: 28 April 2021

Three Industry Sectors

Artisanal Gold Mining

Inorganic mercury (Hg)
Methylmercury (MeHg)
Lead (Pb)

Used Lead Acid Battery Recycling

Lead (Pb)
Cadmium (Cd)

Small-Scale Tanneries

Chromium (Cr)
Chromium VI (CrVI)
Lead (Pb)
Arsenic (As)
Cadmium (Cd)

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Develop a Consistent Format Across Guidelines

Exposure Factors

- Population behaviors, activity patterns, and contact rates
- Section 2: *Study Sampling Design* and Annex 2: Home Survey Questionnaire

Exposure Point Concentration

- Chemical concentrations in environmental media
- Section 3: *General Guidelines for Environmental Sampling*

Internal Dose

- Chemical concentrations in biological matrices – biomarkers of exposure and effect
- Section 4: *General Guidelines for Biological Sampling*

Health Outcomes

- Symptoms, intermediate health outcomes, and health effects
- Section 5: *Guidelines for Medical Survey, Exams, and Diagnostic Testing: Health Outcomes*

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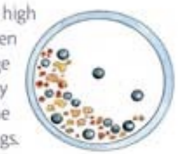
Artisanal Gold Mining - ASGM

Under Annex C of the Minamata Convention, several ASGM practices are considered "actions to eliminate" including whole ore amalgamation and open burning of amalgam.

Whole Ore Amalgamation

Mercury is added to the entire ore, without any previous steps to concentrate the gold from the rest of the ore.

Mercury use is high and inefficient, often resulting in large amounts of mercury being lost to the mine tailings.



Open Burning of Amalgam

Mercury and gold form an amalgam, which is heated to evaporate the mercury. The mercury vapor released is highly toxic.

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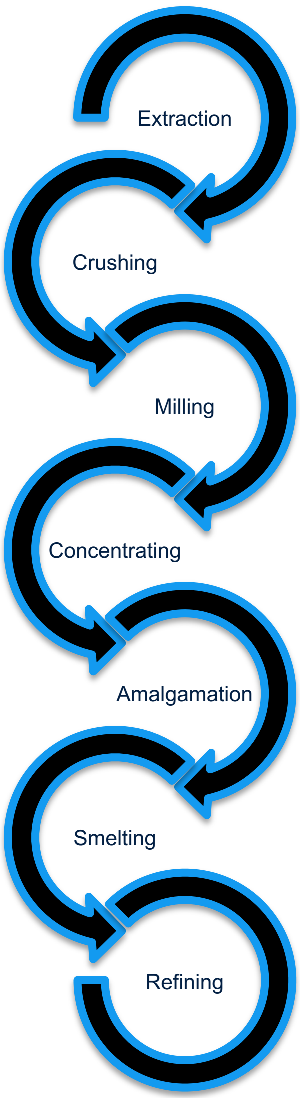
Process Leading to Environmental Releases



Underground mining; sediment pumping from riverbed

Typically done by hand; may be offsite from primary area

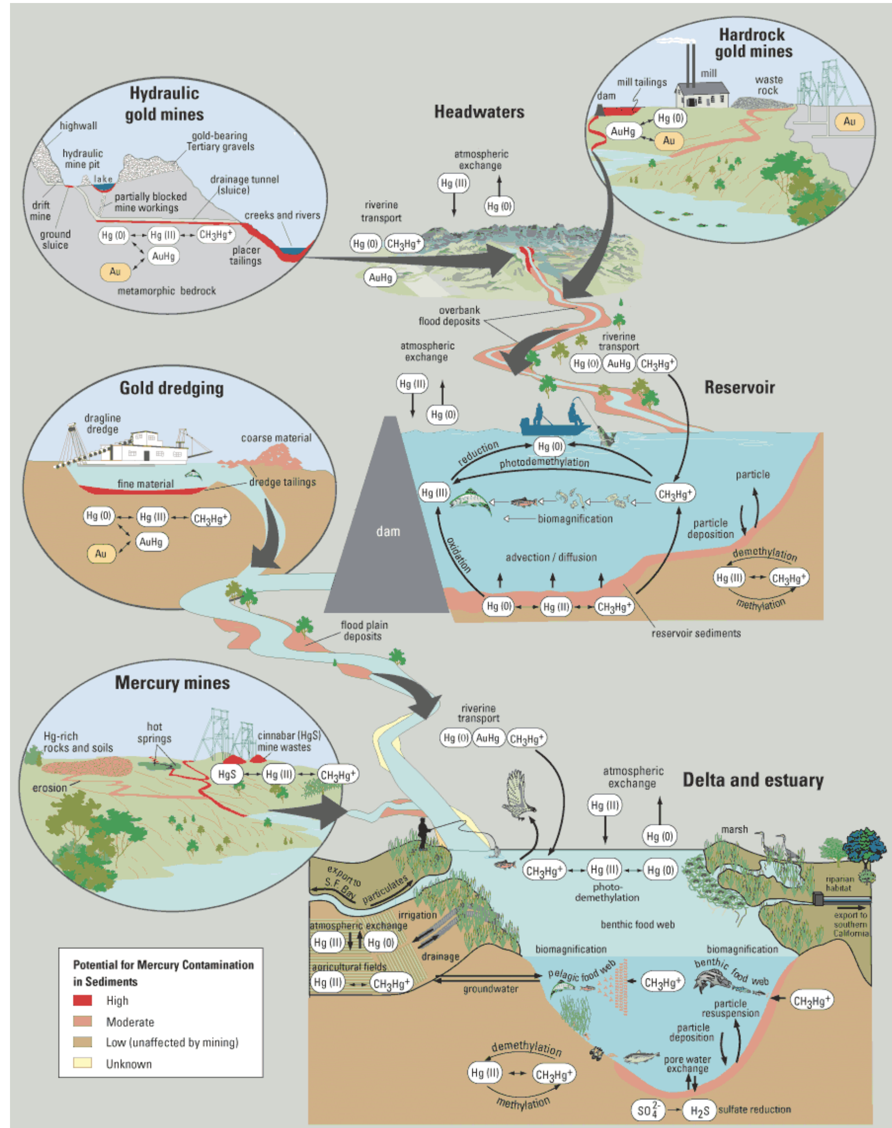
Use of ball mills or other grinding to obtain mineral powder

Hg added to form Hg-gold amalgam

Excess Hg is removed, often by squeezing through cloth with bare hands resulting in 60% gold

Amalgam burned in open pans (fast and easy) or retorts (less Hg vapor)

Gold is heated to vaporize residual Hg. Often done indoors



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Exposures at ASGM Sites

Exposure Route	Environmental Media		
	Air	Soil/Dust	Water
Inhalation	Inhalation of Hg vapors and Hg, Pb, As particles in outdoor air due to releases to air during entire process or during crushing and milling of ore	Inhalation of Hg soil vapors and Hg, Pb, As particles or dust in outdoor air due to releases to soil during entire process or during crushing and milling of ore or from mine tailing or wastewater discharges to water	Inhalation of Hg or Pb vapors released from tap, surface, or ground water (e.g., bathing, showering, washing, swimming) due to mine tailing or wastewater discharges to water
	Inhalation of Hg vapors and Hg, Pb, As particles in indoor air due to releases to air during entire process or during crushing and milling of ore	Inhalation of Hg soil vapors and Hg, Pb, As particles or dust in indoor air due to releases to soil during entire process or during crushing and milling of ore or from mine tailing or wastewater discharges to water	
Ingestion	Ingestion of agricultural products contaminated with Hg, Pb, As due to deposition of vapors or particles (e.g., fruits, vegetables, grains)	Incidental ingestion of Hg, Pb, As in soil or dust (indoors or outdoors) due to releases to soil during entire process or during crushing and milling of ore and from mine tailing or wastewater discharges to soil	Ingestion of Hg, Pb, As in tap, surface, or ground water due to mine tailing or wastewater discharges to water
	Ingestion of agricultural products contaminated with Hg, Pb, As due to transfer of contaminants from air to animals or plants to animals (e.g., meat, milk, eggs)	Ingestion of agricultural products contaminated with Hg, Pb, As by transfer of contaminants from soil to plants, animals, or plants to animals	Ingestion of Hg, Pb, As in agricultural products due to being irrigated with contaminated water
			Ingestion of Hg, Pb, or As in agricultural products due to transfer of contaminants from water to animals
			Ingestion of MeHg in fish/shellfish due to deposition of Hg and methylation to MeHg in sediments
Dermal contact	Dermal contact with Hg vapors and Hg, Pb, As particles due to releases to air during entire process or during crushing and milling of ore	Dermal contact with Hg, Pb, As in soil or dust (indoors or outdoors) due to releases to soil during entire process or during crushing and milling of ore and from mine tailing or wastewater discharges to soil	Dermal contact with Hg, Pb, As in tap, surface, or ground water due to mine tailing or wastewater discharges to water

Used Lead Acid Battery Recycling - ULAB

Draining batteries

- Draining electrolyte from batteries
- Can lead to direct discharges of lead to soil and water
- Purification and treatment of sulfuric acid electrolyte

Cracking and breaking batteries

- Separation of component battery parts in a water bath (lead sinks to the bottom and plastics rise to the top)
- Disposal of plastics can involve burning
- Plastics repurposed without cleaning

Smelting

- Air drying of lead and lead oxide-containing materials
- Mixing material with coal, soda ash, and scrap metal
- Transferring material to uncovered vessels for heating
- Lead fumes condense and settle as particulate

Refining

- Further heating to produce lead ingots
- Solid waste discharged to unlined lagoons or pits
- Wastewater discharged to soil or surface water

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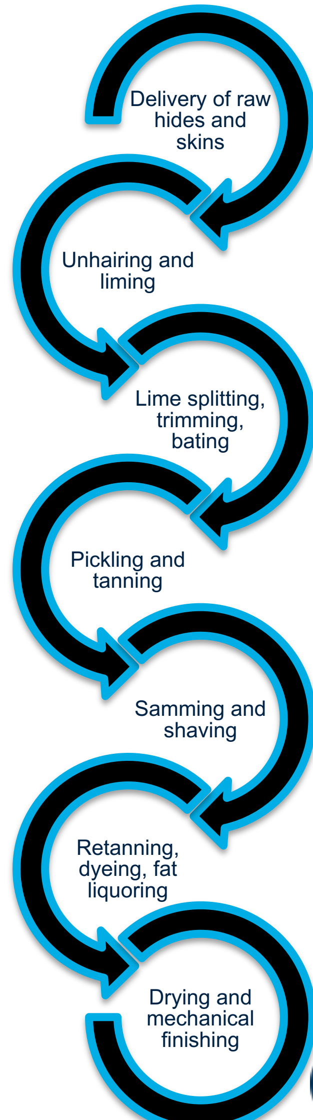
ULAB Exposures

Exposure Route	Environmental Media		
	Air	Soil/Dust	Water
Inhalation	Inhalation of Pb vapors and particles in outdoor air due to releases to air from smelting	Inhalation of Pb soil vapors and Pb, As, or Cd particles or dust in outdoor air due to dismantling batteries, releases to soil from smelting, and solid waste or wastewater discharges to soil	Inhalation of Pb vapors released from tap, surface, or ground water (e.g., bathing, showering, washing, swimming) due to solid waste or wastewater discharges to water
	Inhalation of Pb vapors and particles in indoor air due to releases to air from smelting	Inhalation of Pb soil vapors and Pb, As, or Cd particles or dust in indoor air due to dismantling batteries, releases to soil from smelting, and solid waste or wastewater discharges to soil	
Ingestion	Ingestion of agricultural products contaminated with Pb, As, or Cd due to deposition of vapors or particles (e.g., fruits, vegetables, grains)	Incidental ingestion of Pb, As, or Cd in soil or dust (indoors or outdoors) due to dismantling batteries, releases to soil from smelting, and solid waste or wastewater discharges to soil	Ingestion of Pb, As, or Cd in tap, surface, or ground water due to solid waste or wastewater discharges to water
	Ingestion of agricultural products contaminated with Pb, As, or Cd due to transfer of contaminants from air to animals or plants to animals (e.g., meat, milk, eggs)	Ingestion of agricultural products contaminated with Pb, As, or Cd due to transfer of contaminants from soil to plants, animals, or plants to animals	Ingestion of agricultural products contaminated with Pb, As, or Cd due to being irrigated with contaminated water
			Ingestion of agricultural products contaminated with Pb, As, or Cd due to transfer of contaminants from water to animals
Dermal contact	Dermal contact with Pb vapors and particles due to releases to air from smelting	Dermal contact with Pb, As, or Cd in soil or dust (indoors or outdoors) due to dismantling batteries, releases to soil from smelting, and solid waste or wastewater discharges to soil	Dermal contact with Pb, As, or Cd in tap, surface, or ground water due to solid waste or wastewater discharges to water

Small-Scale Tanneries



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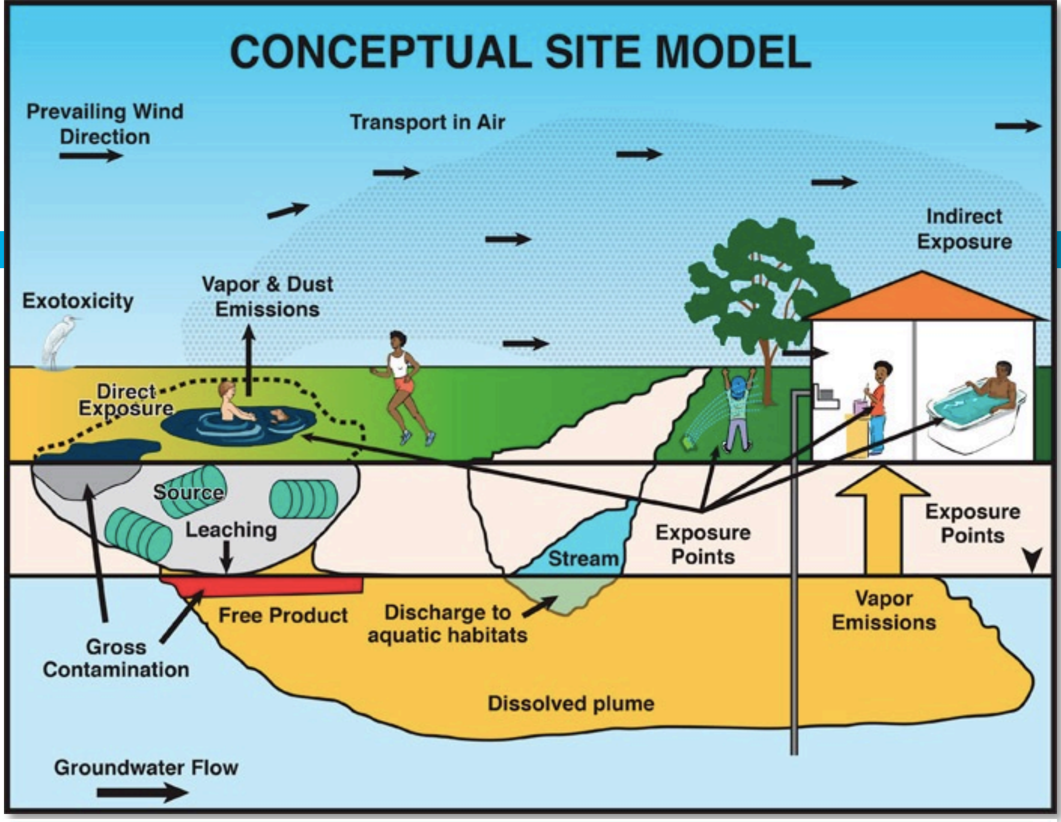
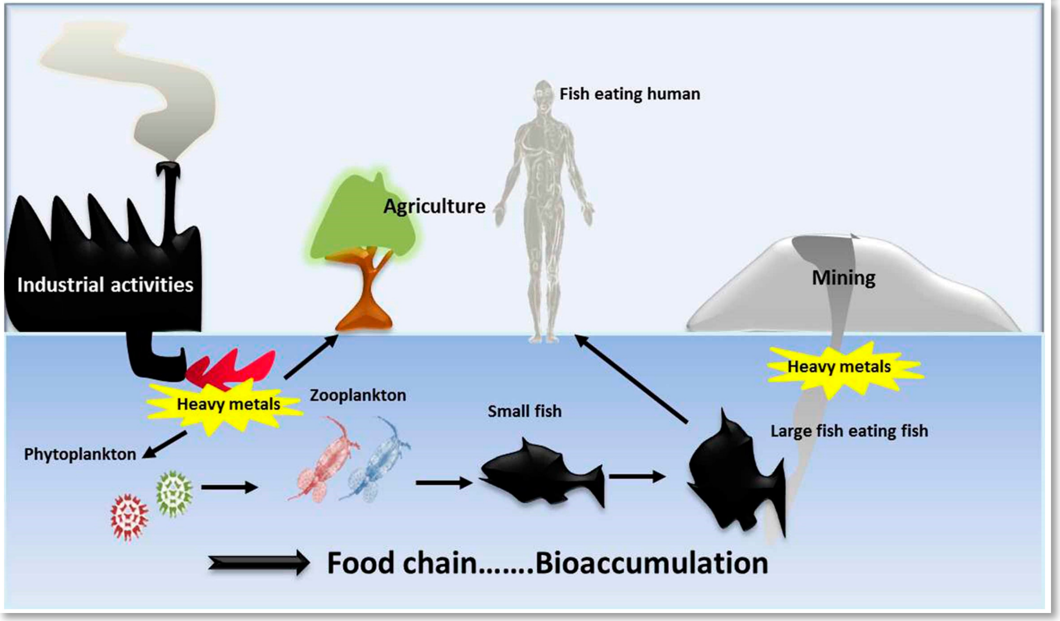
Manufacture of vegetable tanned leather - chemicals used, composition and volume of effluents

	A) Strap and russet upper leather (e.g. belts, handbags, suitcases)			**B) Sole leather**		
Current .Nr.	Operation	Efflu-ent m^3/t	Chemicals used, Effluent constituents	COD % load	Efflu-ent m^3/t	Operation
1	Preliminary Soaking	ca.15	Alkali, wetting agents, biocides, dung, blood, soluble protein, curing salt, AOX	ca.50 %	6 - 8	Soaking
	(Soaking) liming		Lime, Na-sulphide, Na-hydrogen sulphide, residual protein from hair and skin, fat, degradation products			Liming
3	Deliming, Bating, washing		Ammonium sulphate, oxalates, CO_2, citrates, enzymes; epidermis, hair and pigment residues, non-collagenic proteins, soluble lime salts			Deliming, Bating
4	Pit tanning* (removal of content at 4 - 6 week intervals)	ca.8	Vegetable and synthetic tanning agents (A: ca.20 % tanning agent/pelt weight; B: ca. 25 - 30 % tanning agent/pelt weight); leather fibres, organic degradation products,	ca. 50 %	ca. 2	Pit tanning (removal of content at 2 - 6 month intervals)
5	Dripping, washing Samming					Washing, samming
6	Fat-liquoring	1 - 2	Greasing agents, emulsifiers, leather fibres			
7	Retanning, dyeing, greasing washing	ca.5	Vegetable and synthetic tanning agents, dyes, fat, emulsifiers, leather fibres			
8	Samming					
		$\sum$ 15 - 30			ca.10	
	COD ca.150 kg/t, 5000-10 000 mg/l			COD ca. 100kg/t; 10 000-12 000 mg/l		

* Drum tanning used only in split manufacture; here, the volume of waste water is ca. 1 m^3/t raw hides; COD: up to 10000 mg/l; BOD_5: up to 3000 mg/l.





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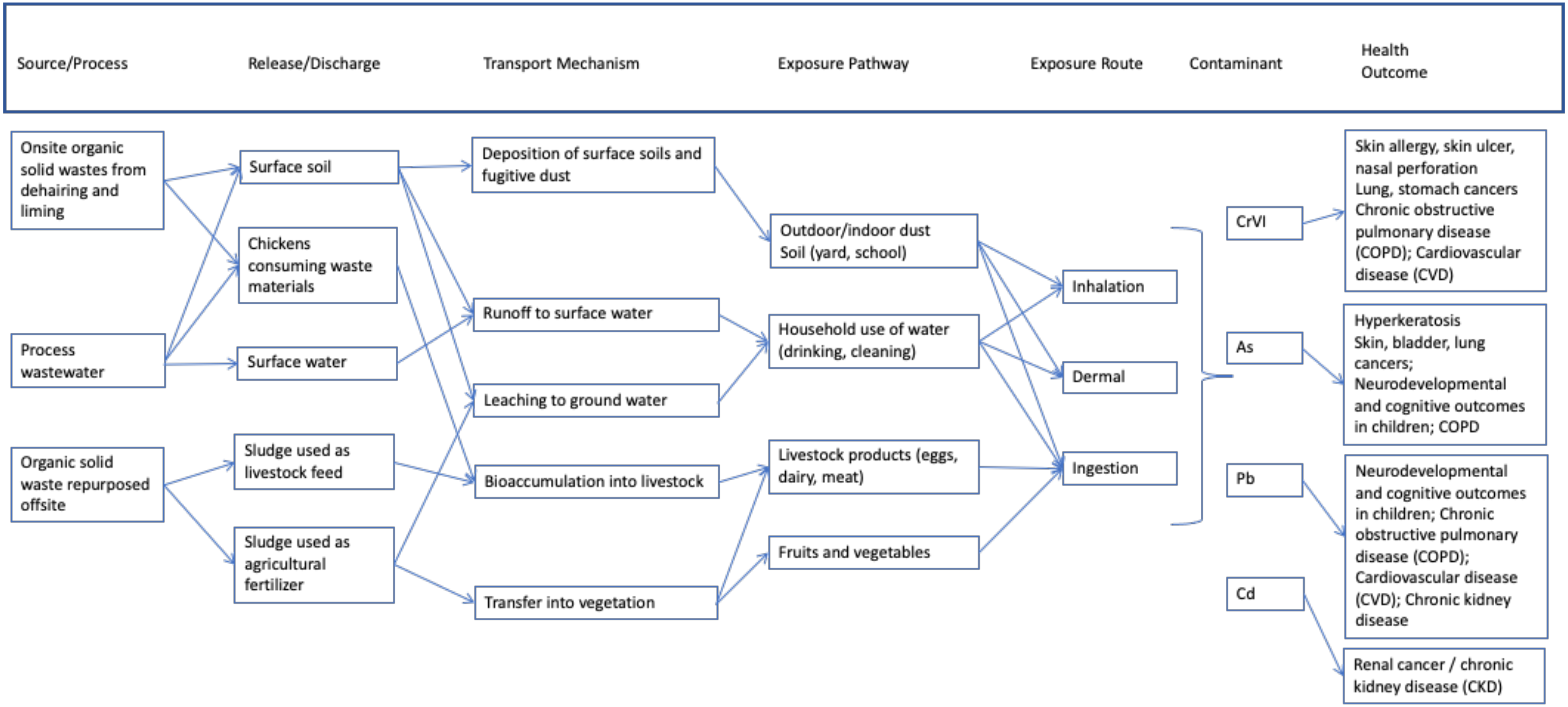

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Generalized Conceptual Site Models (CSMs)

Series of questions as a checklist to make the CSMs site-specific

Community exposures

Environmental setting combined with behaviors and activities

- Fate and transport of contaminants
- Where and how people spend their time
- Vulnerable subpopulations

Process for identifying participating households

- Must be a direct connection between environmental exposures, biomonitoring data, and health outcome data

Focus is on metals but recognize there are many different contaminants (e.g., solvents, pesticides, organics)

Primary contaminant – identifying signal in the noise

Iterative not linear process – may benefit from household survey input

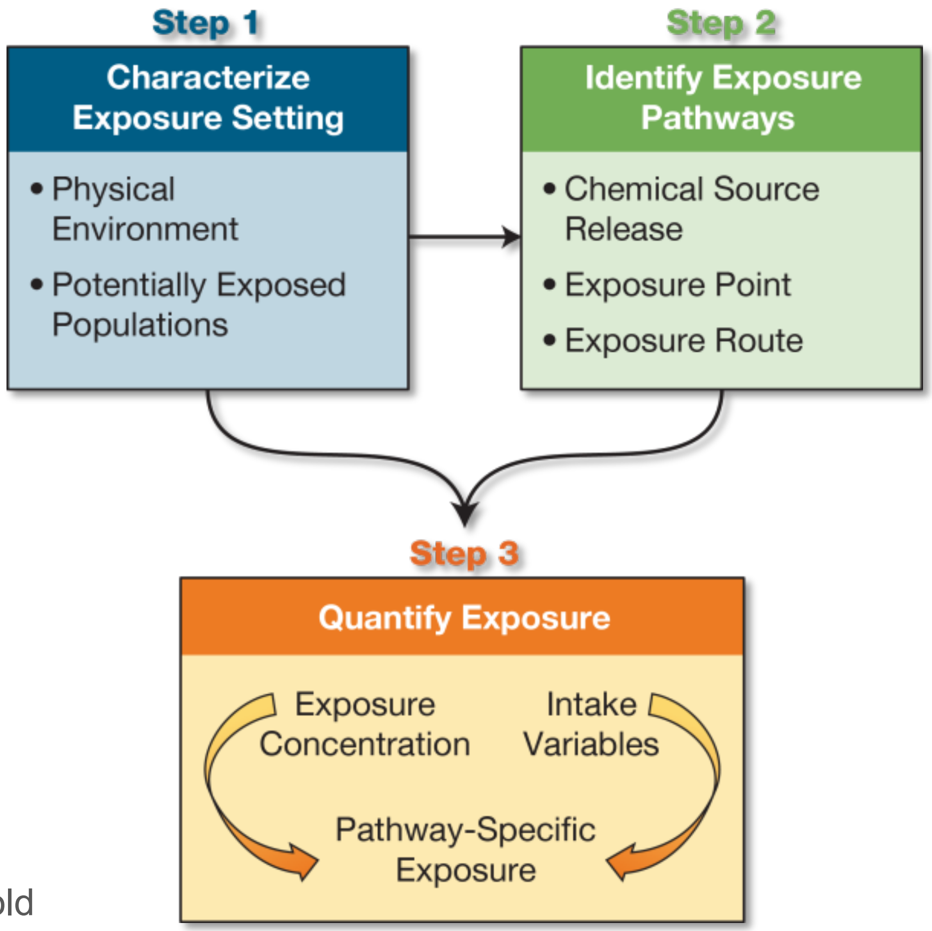

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Table 1. Overview of sector-specific guiding questions.

ASGM	ULAB	Tanning
• Locate ASGM activities in the context of local populations, noting where different aspects of the process may occur. In some areas, grinding and milling occurs in local homes. • Identify locations of all surface waters, including ditches, creeks, streams, rivers, and lakes. • Identify what is known about ground water, depth to the water table and aquifers in the study area. • Identify the prevailing wind direction, particularly relative to residential areas, local waterbodies, and small- or large-scale agricultural activities within several km of primary site activities, particularly amalgamation. • Identify water bodies within a depositional area of ASGM activities, or impacted by wastewaters or soil runoff. • Identify agricultural areas, community gardens, and the potential for backyard gardening. • Locate sources of irrigation water that might be impacted by ASGM discharges, including direct or indirect surface water discharges or releases to soils that can runoff or erode. Establish whether ground water is used for irrigation and whether there is a leaching pathway. • Identify locations where animals or animal products (e.g., milk, eggs) are raised for consumption.	• Locate ULAB activities in the context of local populations, noting where different aspects of the process may occur. In some areas, battery breaking may occur in separate areas from primary smelting and refining. • Identify locations of all surface waters, including ditches, creeks, streams, rivers, and lakes. • Identify what is known about ground water, depth to the water table and aquifers in the study area. • Identify the prevailing wind direction, particularly relative to residential areas, local waterbodies, and small- or large-scale agricultural activities. Dispersion and deposition of lead dust and other metals is likely to be significant, and can occur over large areas. • Identify water bodies within a depositional area of ULAB activities, or impacted by wastewaters or soil runoff, both of which are likely to contain lead and other metals. • Identify agricultural areas, community gardens, and the potential for backyard gardening. • Locate sources of irrigation water that might be impacted by ULAB wastewater discharges, including direct or indirect surface water discharges or releases to soils that can runoff or erode. Establish whether ground water is used for irrigation and whether there is a leaching pathway. • Identify locations where animals or animal products (e.g., milk, eggs) are raised for consumption.	• Locate small-scale tanning activities in the context of local populations. • Note whether process activities are dispersed in different areas, for example, curing and soaking occurring in one location while fleshing and liming occurring elsewhere. In some cases, specific activities will be clustered within smaller neighborhoods. • Identify locations of all surface waters, including ditches, creeks, streams, rivers, and lakes. • Identify what is known about ground water, depth to the water table and aquifers in the study area. • Identify the prevailing wind direction, particularly relative to residential areas, local waterbodies, and small- or large-scale agricultural activities. • Identify agricultural areas, community gardens, and the potential for backyard gardening. • Locate sources of irrigation water that might be impacted by tanning discharges, including direct or indirect surface water discharges or releases to soils that can runoff or erode. Establish whether ground water is used for irrigation and whether there is leaching pathway. • Identify locations where animals or animal products (e.g., milk, eggs) are raised for consumption. Organic wastes from tanning, including residual scrap hides, protein, hair and fur, dung, fatty material, and other organic solid wastes, including chemicals from the tanning process, are often repurposed as either livestock feed or fertilizer. Identify and locate these activities on a map.

Determining the Zone of Influence

Link back to specific objectives (assumes primary objective is linking environmental sampling to biomonitoring data to community health outcomes)

Develop site map based on local land use

Characterize environmental setting

- Detailed checklist
- Individual vs. shared drinking water
- Agricultural products
- Schools, community centers, public gathering

General demographics

- Relative to environmental setting
- Vulnerable populations
- Places where people spend time

Refine the general CSM to finalize site-specific CSM

Collect field data

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Identifying Participating Households

Sample sizes and power calculations

- Highly dependent on specific hypotheses, expected variance
- Multiple contaminants, exposure pathways, health outcomes
- Provide recommendations for how to calculate given specific objectives
- In general – 200-300 households as a working strawman

Overlay a grid on site map

- Recommendations for grid density

Need for targeted sampling

- May require additional input following results of household surveys

Children and youth generally the target population

- But also include adults – renal effects, cancer

Data from Household Surveys

- Stakeholder engagement!!!!!
- Important data source
- Field implementation
- Demographics
- Economics – facilitate later linkages
- Behavior and time-activity patterns: exposure factors
- Self-reported health outcomes
- Limited observations on health outcomes (e.g., skin or other obvious responses)
- Recommend doing this early in the process – may change/augment the CSM, sampling plan and program
- Sets the stage for later (concurrent) environmental sampling, more detailed health outcome data collection, biomonitoring

Environmental Sampling

Media- and contaminant-specific

Emphasize use of in-field XRF

- 25% confirmatory samples sent to a laboratory – local laboratory
- Subset of samples for focused analyses, such as bioavailability of As, Pb and CrVI
- Hg vs MeHg in environmental samples

Recommendations related to site-specific CSM

- Agricultural products
- Fish and fish consumption
- If site-specific study objectives call for understanding bioaccumulation, then water, sediment and fish sampling should occur

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Biomonitoring Data

Contaminant	Recommendations
As	Gold standard is metabolite monomethylarsonic acid (%MMA) obtained from a speciated creatinine-adjusted urine sample
Cd	International consensus on use of creatine-adjusted urine
Cr (CrVI)	Red blood cells or urine; can speciate. Recommend hair given non-occupational exposures
Hg	In-field XRF (toenails) together with blood
MeHg	Hair and in-field XRF
Pb	Venous blood is the gold standard but dried capillary blood spot also used, which allows in-field LeadCare analyzer

Health Outcomes

Metals	Measurable Health Outcomes
Hg	Developmental and cognitive deficits in children Neurotoxicity (e.g., tremors, ataxia) in children and adults Renal health outcomes in children and adults
MeHg	Developmental and cognitive deficits in children
Pb	Developmental health outcomes in children (e.g., reduction in IQ, cognitive deficits) Cardiovascular health outcomes in adults Renal health outcomes in children and adults
CrVI	Renal health outcomes in children and adults Lung, bladder, and gastrointestinal (GI) tract cancers in adults
As	Skin rashes and lesions and hyperkeratosis, possible precursors to skin cancer Developmental and cognitive deficits in children Lung cancer in adults Bladder cancer in adults
Cd	Nephrotoxicity and renal effects, possible precursors to kidney cancer

Measuring Health Outcomes

Category	Utility and Examples
Formal medical diagnosis or clinical testing	Related to direct or measurable clinical outcomes known to be associated with exposure • bladder cancer or hyperkeratosis associated with As exposures • cognitive deficits as measured by age-specific standardized testing instruments associated with exposures to MeHg, Pb, and As
Intermediate, non-specific observation or measurement	Associated with the health outcome of interest • increased blood pressure associated with cardiovascular outcomes that may be related to exposure to Pb, MeHg, Cd
Intermediate biochemical measurement or biomarker of effect	Laboratory or in-field analysis of a biological matrix • diagnosis of anemia based on hematocrit level in blood that may be related to Pb exposures • micronucleus formation in blood that may be associated with genotoxic effects of As

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Contaminant-Specific Recommendations

CoC	Biomonitoring (Exposure)	Health Outcomes
As	Gold standard is metabolite monomethylarsonic acid (%MMA) obtained from a speciated creatinine-adjusted urine sample	• Conduct age-specific, culturally-relevant cognitive testing for each child • Conduct in-field screening for keratosis on the soles of the feet as part of the household survey or as part of a more formal medical examination • If keratosis is observed, consider a carcinogenic biomarker such as DNA adduct assay or micronucleus formation assay • Measure C-reactive protein as a non-specific biomarker of intermediate effects on the renal and cardiovascular systems
Cd	International consensus on use of creatine-adjusted urine	• Measure sensitive urinary biomarkers, including β2-m (urinary β2-microglobulin), and glomerular filtration rate (GfR) • If elevated, consider measuring additional carcinogenic biomarkers, such as DNA adduct formation or micronucleus formation
Cr (CrVI)	Red blood cells or urine; can speciate. Recommend hair given non-occupational exposures	• Evaluate CrVI-induced ulceration of the nasal septum mucosa and potential for skin allergies as demonstrated through skin rashes on the hands and feet • If dermatological symptoms are observed, consider patch-testing for individuals with dermatological symptoms • Consider measuring carcinoembryonic antigen (CEA; a non-specific biomarker of gastrointestinal cancers) in individuals with dermatological symptoms • Conduct limited pulmonary function testing (PFT) and measure C-reactive protein (CRP; a non-specific inflammatory biomarker in blood associated with lung, kidney, and cardiovascular outcomes)
Hg	In-field XRF together with hair	• Administer the CIMI as presented in Table 5-2 to each participant (can be done in-field with appropriately trained personnel or as part of a more formal clinical assessment) • Measure proteinurea (e.g., albumin)
MeHg	Hair	• Conduct age-specific, culturally-relevant cognitive testing for each child
Pb	Venous blood is the gold standard; dried capillary blood spot also used, allows in-field LeadCare Analyzer	• Measure blood pressure in adults in the field or as part of a medical examination • Measure specific biomarkers including proteinuria (e.g., albumin), anemia status (e.g., hematocrit), cardiovascular risk (e.g., C-reactive protein) • Conduct age-specific, culturally-relevant cognitive testing for each child

Conclusions

Guidelines geared toward a specific objective: understanding potential health outcomes at the community level as a function of specific land-based pollution sources

- Maximize likelihood of discerning signal from noise

But can be used to achieve multiple and varying sub-objectives

- Biomonitoring data – measurement and repository
- Comprehensive environmental characterization and setting
- Expanding local capability – laboratory analysis to conducting surveys to health outcome measurement
- Database of exposure factors

Depending on emphasis, need to carefully think through power and sample size calculations

- Guidelines do not address statistical methods and analyses
- Linkages to economic data

Moving Toward Solutions

Consistent data collection will improve understanding and implications of land-based pollution

There should be a plan / consensus on anonymized data repositories

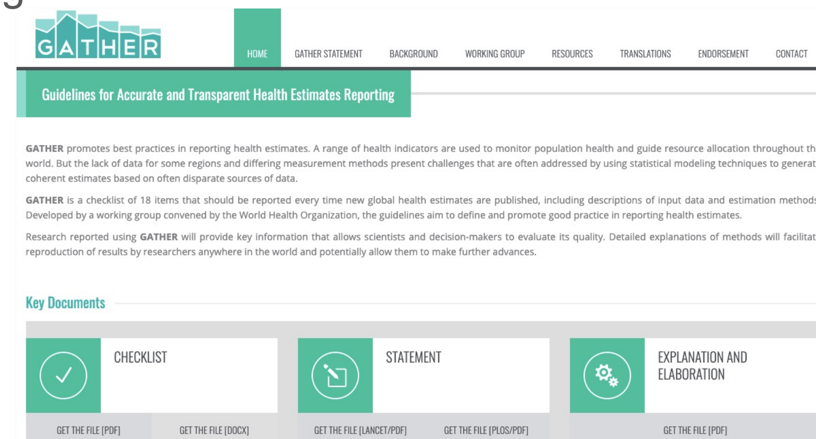
Exposure Factors Handbook

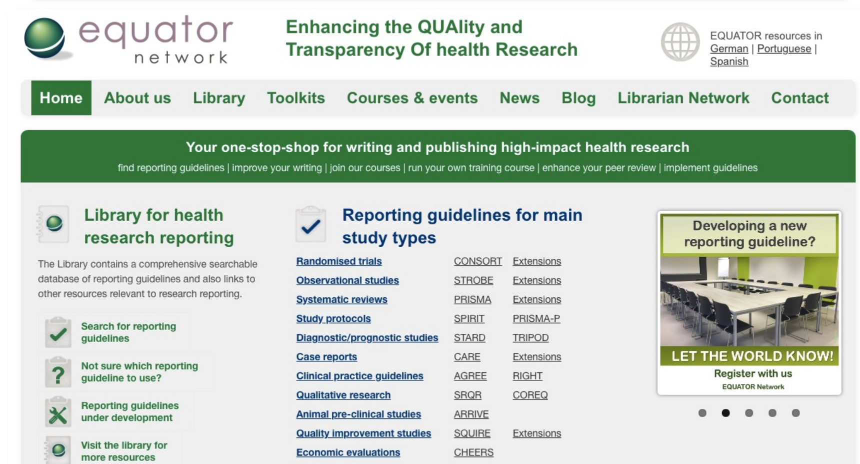
How “big” is the problem

Can use the process to engage community and strengthen understanding of issues

Elicit community preferences

Support systems-based management approaches: Ecosystem services, climate change, transformation





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