

## Key Points:

- Artisanal and small-scale mining (ASM) is primitive with health problems determined by occupational, environmental, and social settings
- ASM involves 80 + countries and valuable resources, like gold, diamonds, precious stones, tantalum, tin, tungsten, and commodities
- Grueling work, poverty, illegalities, and worksites located in remote and medically underserved areas contribute to poor health

## Correspondence to:

F. W. Schwartz,  
schwartz.11@osu.edu

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# A Review of the Scope of Artisanal and Small-Scale Mining Worldwide, Poverty, and the Associated Health Impacts

Franklin W. Schwartz<sup>1,2</sup> , Sangsuk Lee<sup>1,2</sup>, and Thomas H. Darrah<sup>1,2</sup>

<sup>1</sup>School of Earth Sciences, The Ohio State University, Columbus, OH, USA, <sup>2</sup>Global Water Institute, The Ohio State University, Columbus, OH, USA

**Abstract** Some of the poorest people in the world's poorest countries eke out a living in artisanal and small-scale mining (ASM). Equipped with primitive tools like picks, shovels, buckets, and gold pans, they work mining valuable resources, like gold, diamonds, tin, lithium, rare earth elements, tantalum, and cobalt, and any other usable commodity, for example, sand, coal, or mica. The mining and refining processes are labor intensive and associated with a variety of health problems due to accidents, overheating, overexertion, dust inhalation, exposure to toxic chemicals and gases, violence, and illicit and prescription drug and alcohol addiction. Evident disadvantages with ASM are counterbalanced by the immense economic benefits. For many, the true scope and scale of ASM activities are unappreciated, along with the unknown health and societal impacts. Here, we set out to elucidate the scope of ASM beyond the recovery of familiar commodities, such as gold and diamonds. We adopt a holistic perspective toward health impacts of ASM, which includes unique occupational, environmental, and human/social drivers. A particular focus is poverty as a health risk with artisanal miners. They are commonly poverty-stricken people in poor countries, ensnared by a variety of poverty traps, which take a toll on the health and well-being of individuals and communities. ASM sometimes provides an opportunity to diversify income in the face of a decline in subsistence agriculture. However, ASM often trades one kind of generational poverty for another, coming along with serious health risks and turmoil associated with work in an informal “cash-rich” business.

**Plain Language Summary** Many of the world's most valuable commodities, for example, gold, diamonds, and strategic metals, and less valuable resources, for example, sand, clay, and coal, are the products of artisanal and small-scale mining (ASM). The miners are commonly poor people with rudimentary tools, like shovels, buckets, and pans subsisting by working shallow ore deposits. Although an inefficient mining method, the large numbers of people can contribute substantially to a country's total production. Much of this mining occurs in distant, lawless areas like the Amazon River basin or the outback in the Democratic Republic of Congo. The work is grueling and dangerous because of violence and unregulated work sites. Miners suffer from the expected collection of occupational health risks, due to, for example, accidents, chemical exposures, dust inhalation, and lifting and lugging of heavy loads. Mining communities are at risk from incidental exposures to mercury, mosquito-borne diseases, poor sanitation, and more. Human and social problems also impact health. Our paper emphasizes poverty as a risk factor for disease, as miners are caught in poverty traps—unable to leave. Injuries and disease often must remain untreated because of costs and absent clinics.

## 1. Introduction

Not all mining is done by large companies deep below ground or with expensive machinery in large open pits. Worldwide, millions of people labor with primitive tools, picks, shovels, and pans to extract valuable natural resources from the Earth. This workforce of artisanal and small-scale miners is commonly itinerant, without much education or training. The idea that artisanal and small-scale mining (ASM) is actually not small is the theme of a recent commentary in *The Lancet Respiratory Medicine* (Burki, 2019). It cites commonly reported global estimates of 40 million people in 80 countries (IISD, 2017), as compared to the approximately 7 million people in “industrial mining.” An estimated 150 million people are dependent upon the ASM industry (IISD, 2017). Although ASM is inefficient, it contributes 20% to 25% of the world's annual production of gold, diamonds, tin, tantalum, and cobalt. The mining and refining processes in the poorest countries are primitive, labor intensive, and associated with numerous health problems (Burki, 2019). The list of health hazards is long, including accidents, heat, overexertion, dust inhalation, exposure to

toxic chemicals and gases, illicit drug, prescription drug (e.g., painkiller), and alcohol addiction, and various forms of violence (WHO, 2016). However, the societal detriments are counterbalanced by the immense economic importance of ASM. It is widely considered to be “indispensable” and “the most important nonfarm activity in the developing world” (World Bank, 2019). For poor nations, it often provides an important opportunity for alleviating problems of rural poverty (World Bank, 2019).

The challenge in realizing the economic potential of ASM is with formalization and regulation (Debrah et al., 2014). The term formalization refers to codifying ASM in a government’s legal and economic framework with, for example, policies around mineral rights, taxation, environmental regulations, and workplace safety (de Theije & Salman, 2018; Siegel & Veiga, 2010). ASM has operated for centuries as a small unorganized and informal activity. For example, Allchin (1962) discusses small- and large-scale gold mining that operated in India from 100 BCE to 300 CE. Similarly, “folk” mining in Colombia was an important source of gold for Spain from the sixteenth to eighteenth centuries. North American examples of folk mining include the Carolina Gold Rush (1799–1832), the California Gold Rush (1848–1855), and the Klondike Gold Rush (1896–1899). Since those days, ASM activities exploded around the world to the extent that both the negative and positive impacts are now too large to ignore. Yet, the activity remains informal, because attempts at management have produced minimal outcomes at a global scale, specifically within poorer countries (Debrah et al., 2014).

We prepared this targeted review of ASM for several reasons. First, the true scope and scale of ASM activities are generally unappreciated, particularly the health and environmental impacts. Second, it is our concern that these negative impacts may continue growing without realizing the potential economic benefits in reducing problems of rural poverty. This paper aims to elucidate the scope of ASM, especially outside of the more familiar commodities, such as gold and diamonds. We also examine health impacts of ASM from a holistic perspective that includes occupational, environmental, and human/social drivers.

The emphasis on the human/social determinants of health is because two of the major risk factors, poverty and violence, come along with ASM. This paper explains how poverty is associated with ASM and its growth and what causes poor people to stay poor. A companion paper continues with discussions of the health risks associated with child labor and violence.

## 2. The Problems of Data and Resource Management

A 2019 assessment of ASM is candid in its assessment of just how little information is available (World Bank, 2019). Beyond outdated estimates of how many people work in ASM, and production numbers, there are little other publicly available data. Data holes include information on the structure of the industry worldwide, the demographics of individuals and communities associated with ASM, and characteristics of the value chains responsible for moving commodities from mines to world markets.

This data gap has existed for at least 40 yr with a disturbing tendency to recycle numbers (World Bank, 2019). Because of the paucity of data, it is unclear how market forces, like commodity prices or socioeconomic drivers, affect the workforce or the capacity for developing regulation (World Bank, 2019). These issues do not bode well for attempts to formalize ASM. Simply put, it is difficult to properly manage any activity that is not well understood.

Some researchers interpret this data problem for ASM as simply inattention or a lack of resources deployed for getting out to gather needed information (e.g., World Bank, 2019). However, the World Bank’s experience with the managements of groundwater and surface water resources in developing countries makes it clear that data problems relate to a much larger problem—namely, countries’ inability to provide a framework for action or the capacity to manage ASM activities.

For groundwater, key elements of the framework include (i) a governmental vision of needed solutions to the problem that leads to (ii) policies and laws that provide governments with the powers and instruments needed to manage the resource (Garduno & Foster, 2010; Smith et al., 2016). In ASM, powers might include mandated registration of claims, managing production on a continuing basis through licenses, creating government-sponsored supply chains, and enforcing mining bans in environmentally sensitive areas or national parks. Successful management requires governments to be proactive in developing acceptance

among stakeholders and punishing noncompliance with the general policies, as well as pollution and safety violations (Smith et al., 2016).

There is some progress among ASM countries, for example, South Africa and Ghana (Debrah et al., 2014), in creating a framework for managing ASM. However, to make this all work requires strong oversight of activities in the field. For groundwater management, such oversight is lacking primarily because of indifference to the problems and a lack of capacity (Schwartz et al., 2020). Similarly, with ASM, oversight is lacking for the same reasons. There is indifference because ASM often operates in poorly accessible locations outside of state control (de Theije & Salman, 2018). For example, in the Madre de Dios region of the Amazon River, “the central government in Lima is not really interested in the miners, or in the region, and gives no priority to combating illegal small-scale mining” (de Theije & Salman, 2018). Poorer countries also often lack the capacity to enforce laws.

Only when there is a robust management structure should there be expectations for reliable or relevant data. The challenge of operational management in the field is difficult for groundwater but impossible for poor countries with rich mineral resources, where the business aspects of ASM are commonly illegal and violent, as discussed in our companion paper. Thus, the result for ASM is a paucity of data with few present prospects or directives for change.

### 3. Resources Targeted With ASM

#### 3.1. Mining Techniques

ASM usually targets high-value commodities (Dorner et al., 2012), such as placer deposits containing gold, diamonds, colored stones, or tin weathered from bedrock. Placer deposits are commonly alluvial sands and gravels rich in precious metals or gemstones. Modern or older settings include overbank flow deposits, riverbank terraces, or in-bank deposits. The basic tool kit for placer mining includes shovels, pans, buckets, and homemade sluice boxes for gold. Thus, individual miners can only process small quantities of materials each day with only a chance for small and inconsequential returns.

Over the last three decades, small-scale gold mining involving a crew with mechanization has become more common, for example, in Colombia (Masse & McDermott, 2017). Equipment might include high-pressure water cannons for knocking down riverbanks for sluicing, backhoes, and river dredges. Processing much larger volumes of material naturally leads to much greater gold returns. Such mining is less artisanal because of the significant investments required in mechanical implements and machinery. Also, it can be criminal, with control by illegal actors, a blatant disregard of environmental laws and traditional claims, or with illegal work practices.

Another target for ASM is small lode deposits that are uneconomic for large companies (Dorner et al., 2012). This mining is more challenging because miners need to dig mineshafts, work underground, and bring ore-bearing rocks out of the mine for processing. Lode deposits can include gold and a variety of other precious metals, precious stones, or sedimentary deposits like coal. Artisanal miners access these deposits through crude, poorly supported shafts without proper supports and ventilation. One notorious example is the “rathole” coal mines of northeastern India (Ghosh, 2018).

#### 3.2. Scope and Scale

ASM activities are amazingly broad in terms of the countries involved and the variety of commodities mined. We organize the discussion here within three major categories: metals, diamonds and colored stones, and industrial or other materials (Table 1).

##### 3.2.1. Metals

In the metals category, gold is the most economically important on a global scale with ASM activities in approximately 60 to 70 countries (Seccatore et al., 2014; WHO, 2016). Table 1 lists countries with significant artisanal gold production in Asia, Africa, and South America. Asia produces approximately 120 t (metric tonnes) of gold annually with China, Indonesia, Pakistan, Philippines, and Vietnam as the major producers (Seccatore et al., 2014). Some 36 countries in Africa have gold production with Burkina-Faso, Democratic Republic of Congo (DRC), Ghana, Madagascar, South Africa, Sudan, and Tanzania as the most relevant producers. Estimates of production for Africa are uncertain, ranging from 85 t (Seccatore et al., 2014) to 250 t annually. The larger value accounts for apparently larger production in DRC, Ghana, Sudan, and

**Table 1**  
*A List of Commodities of Interest in ASM, the Forms in Which They Occur, and Examples of Countries in Which Mining Occurs*

Commodity	Form	Key countries
<b>Metals</b>		
Gold—Asia	Au	China, Indonesia, Pakistan, Philippines, Vietnam
Gold—Africa	Au	Burkina-Faso, DRC, Ghana, Madagascar, South Africa, Sudan, Tanzania
Gold—South America	Au	Bolivia, Brazil, Colombia, Ecuador, Peru, Venezuela
Tantalum (coltan)	tantalite and columbite	Brazil, Burundi, Colombia, DRC, Ethiopia, Nigeria, Rwanda, Venezuela
Tin	cassiterite	Bolivia, China, DRC, Indonesia, Rwanda
Tungsten	wolframite	China, Colombia, DRC, Rwanda
Cobalt	heterogenite	DRC
<b>Diamonds and colored stones</b>		
Diamonds	carbon	Angola, Brazil, CAR, DRC, Ghana, Guyana, Sierra Leone, Tanzania, South Africa, Venezuela, Zimbabwe
Emeralds	beryl	Afghanistan, Brazil, Colombia, Zambia, Zimbabwe
Ruby	corundum	Kashmir, Madagascar, Mozambique, Myanmar, Sri Lanka Thailand
Sapphires	corundum	Kashmir, Madagascar, Myanmar, Sri Lanka, Tanzania, Thailand
Semiprecious Stones	120 + varieties	Sources worldwide
<b>Industrial and other materials</b>		
Aggregates	mostly sand	China, India, Indonesia, Malaysia, Thailand Cambodia
Coal	carbon	India, China, Pakistan
Fossils	various	Siberia, Morocco, China, Brazil
Sulfur	S <sub>2</sub>	Indonesia

Tanzania than the estimates of Seccatore et al. (2014). Worldwide, ASM contributes roughly 20% of total gold production. For perspective, taking a conservative price of \$1,250 (USD) per troy ounce and the reported 2019 gold recovery of ~4,775 t of gold, we estimate that ASM gold mining alone accounts for more than \$38 billion dollars (USD) in direct gold sales in that year.

Next on Table 1 are the “3Ts”—tantalum, tin, and tungsten. These materials underpin industrial applications in electronic, automotive, aviation, and medical industries (Barume et al., 2016). They provide necessary solders, capacitors, microchips, wires, and electrical components. Tantalum occurs as tantalite [(Fe, Mn) Ta<sub>2</sub>O<sub>6</sub>] and other tantalum minerals. The informal term coltan describes ore concentrates of tantalite and columbite [(Fe, Mn) Nb<sub>2</sub>O<sub>6</sub>] (Barume et al., 2016). ASM for coltan occurs mostly in Africa, especially Burundi, DRC, and Rwanda, and in South America (Table 1). Tin comes from the mineral cassiterite, SnO<sub>2</sub>, with artisanal mining mostly in Bolivia, Brazil, China, Indonesia, Myanmar, and to a lesser extent in DRC and Rwanda (Barume et al., 2016). Tungsten occurs as the mineral wolframite, [(Fe, Mn) WO<sub>4</sub>], with ASM in China and some in Colombia, DRC, and Rwanda.

The “conflict minerals,” 3Ts and gold (3TG), as ore concentrates and metals, are subject to various laws and regulations, for example, the Dodd Frank Act Section 1502 (Barume et al., 2016). These laws require companies to establish conflict-free supply chains to meet their 3TG needs. Section 1502 is targeted toward DRC and adjoining countries where mining funded violent conflicts with extreme violations in human rights. However, new laws expected in the European Union (EU) and customer sensitivities are forcing customers to examine potential issues in 3TG supply chains outside of Africa.

Cobalt is critical for the production of rechargeable lithium batteries. Approximately 60% of the world’s annual supply comes from the DRC including 15–20% from ASM (Kennedy, 2020). What makes ASM feasible for cobalt is its occurrence at shallow depths as the mineral heterogenite (CoOOH) (Banza Lubaba Nkulu et al., 2018). Kara (2018) estimates there are 255,000 diggers at work in DRC mining cobalt, including 35,000 children.

### 3.2.2. Diamonds and Colored Stones

Diamonds are the most important gem material in this category. Most of the world’s supply comes from large diamond mines. Five of the top 10 mines are located in Russia, and two are in Botswana with others in





**Figure 1.** Placer mining for alluvial diamonds at the Kenenday mine site, Guinea, with artisanal miners washing gravels (7 March 2012). Credit: Peter Chirico, United States Geological Survey. Public Domain.

Angola, Canada, and South Africa (Mining Technology, 2019). Diamonds occur in both kimberlite pipes, river-associated deposits on land, and shelf deposits under the ocean. In southern Africa, rivers transport diamonds to the western shelf of the South Atlantic Ocean (Garnett, 2002).

Diamonds recovered by ASM come mostly from various types of alluvial placer deposits. For example, in the Central African Republic, there are an estimated 50,000 to 100,000 ASM workers mining alluvial diamonds (Chirico et al., 2010). Miners access diamond-bearing gravels via hand-dug open pits, vertical shafts, diving from boats, and building dikes to expose river gravels (Priester et al., 2010). Figure 1 shows three artisanal miners in a pit washing gravels for diamonds at the Kenenday mine site in western Guinea. At this location, approximately 4 m of overburden needs to be removed to access 0.5 m of productive gravels (Chirico et al., 2014). Artisanal miners also work in abandoned mines, hand-digging in kimberlite pipes and spoil piles. As shown in Table 1, placer diamonds occur in countries across Africa and South America.

“Conflict” or “blood” diamonds have funded civil wars or conflicts in African countries, such as Angola, Sierra Leone, and Zimbabwe. The Kimberley Process Certification Scheme began in 2003 to prevent conflict diamonds from financing wars (Howard, 2016). Although somewhat successful, conflict diamonds remain available to terrorist groups in Africa today (Rush & Rozell, 2017).

Emeralds, rubies, and sapphires are the best-known colored stones. Emeralds belong to the beryl  $[\text{Be}_3\text{Al}_2(\text{SiO}_3)_6]$  mineral family and are commonly found in Colombia and Brazil (Table 1). In Colombia, the industry

is formalized around large companies to the detriment of the ASM, which is declining (Franco et al., 2018). Large companies also mine emeralds in Zambia with associated ASM and illegal looting of mines and mine spoil (Gilberthorpe et al., 2016).

Ruby is a red-colored corundum mineral,  $\text{Al}_2\text{O}_3$ . Mining occurs artisanally in Madagascar, Mozambique, Myanmar, Tanzania, and Thailand. Many precious rubies also come from open pit and underground mines in Myanmar (Burma) (Shor & Weldon, 2009). Madagascar has developed recently as an important source for rubies as production in Asia has declined (Shor & Weldon, 2009).

Sapphire is a blue/pink corundum gemstone found along with rubies, for example, in Myanmar, Thailand, and Madagascar. Sapphire from Kashmir (India and Pakistan) commands some of the highest prices and production (Shor & Weldon, 2009). Issues of ethical and socially responsible sourcing are concerning, particularly in Myanmar and Madagascar, with undisclosed “doctoring” of lower-quality gemstones (Shor & Weldon, 2009).

The semiprecious stone category (Table 1) includes an amazing number of valuable rocks, minerals, and other materials, which represent significant opportunities for ASM. Colored stones in this category include andesine-labradorite feldspar, garnet, jade, opal, peridotite, quartz (amethyst, citrine, and rose) spinel, and tourmaline. Shigley et al. (2010) provide a comprehensive discussion of gem sources worldwide with a list of locations.

### 3.2.3. Industrial and Other Materials

The last category (Table 1) includes illustrative examples of important industrial and other materials. It includes materials (e.g., clay, quartz, and aggregates) for the world’s infrastructure needs, coal, and several other useful earth materials.

Aggregates (mostly sand) are an important commodity with ASM. They are broadly distributed geographically in rivers, lakes, and associated paleocoastlines. Population growth in Asia and Africa and trends in urbanization are powering an enormous demand for construction materials, as well as glass and semiconductors (Bendixen, Best, et al., 2019). Estimates in annual production range from 35 to 50 billion metric tonnes annually (Koehnken et al., 2020) but are likely higher (Bendixen, Best, et al., 2019).

Notwithstanding the environmental impacts, the greater concerns are that demands will soon exceed supplies, and there will be a rush to exploit sand resources on Greenland (Bendixen, Overeem, et al., 2019; Mahadevan, 2019) or in other rapidly deglaciating areas.

The list of countries involved with sand mining (Table 1) is illustrative because studies tend to focus on egregious examples of overproduction, environmental impacts, and violence. China is by far the greatest consumer of sand with a 440% increase from 1994 to 2012 as compared to 60% for the rest of the world (AMAP/UNEP, 2013). In 2012, China's worldwide share of the sand market was approximately 58% (AMAP/UNEP, 2013). Between 2011 and 2013, China's consumption of sand was stunningly equivalent to that of the United States during the entire twentieth century (Koehnken et al., 2020).

The sources for sand in China are likely small-scale efforts aided by dredges and barges. Within China, Poyang Lake is notable as the world's largest sand mine with recoveries from 2005–2006 of 236 million  $\text{m}^3 \text{yr}^{-1}$  (de Leeuw et al., 2010). Other important sources are deposits from the Mekong River in both China and downstream countries (Forsyth & Hruby, 2017).

Accelerating urbanization of India will produce “enormous demands on finite sand reserves” (Mahadevan, 2019). Eventually, their patterns of utilization should end up similar to China. “Sand mafias” currently control sand mining operations in India (Mahadevan, 2019). These “disorganized” collections of “criminal gangs” and “organized villagers” manage mining with liberal applications of bribery and violence as needed (Mahadevan, 2019). Typically, the miners themselves are poor and work by diving to the bottom of rivers to scoop sand into buckets and swimming back to the surface (Mahadevan, 2019).

Land reclamation provides another important use for sand. For example, Singapore used sand to expand its land area by 20% from 1960 to 2017 (Koehnken et al., 2020). It is the world's largest importer of sand, a record that will continue into the next decade (Koehnken et al., 2020). Sand comes from nearby Indonesia, but Malaysia, Thailand, and Cambodia are also major suppliers (UNEP, 2014).

Artisanal mining for coal occurs in most poor and many wealthy countries with deposits. These activities are often invisible except when violence or accidents are newsworthy. Many thousands of people in India make their living on the edges of a feudal and corrupt industry. In northeastern India, people in and around Dhanbad scavenge coal from illegal mines and transport it on foot or by bicycles to depots run by the “coal mafias” (Daniel & Williams, 2013). Coal bosses run unions that charge workers to work, control access to jobs, fix prices for the coal, and extort money from buyers to load coal (Daniel & Williams, 2013). When necessary, miners also dig tunnels to access the coal. These kinds of operations were pervasive in the United States and Canada from the late nineteenth through midtwentieth centuries.

The State of Meghalaya in northeastern India, north of Bangladesh, is a center for “rathole” mining. This practice involves digging a vertical shaft downward to a coal seam then creating small adits into the coal seam. These tunnels are small, earning their rathole name, and are worked by crawling or lying down, using pickaxes to conduct the actual mining (Ghosh, 2018). In December 2018, 15 miners died from flooding of a deep rathole mine. This dangerous mining practice includes women and possibly as many as 70,000 children (Ghosh, 2018). Similar approaches were employed in anthracite coalfields throughout the Appalachian region in the United States in the early twentieth century.

The last two entries are minor ASM activities noteworthy for the ingenuity of people to take advantage of valuable commodities. Since trade in ivory from elephants became illegal in 1989, artisanal miners prospect for skeletal remains of extinct mammoths in Siberia (Farah & Boyce, 2019). They use hydraulic mining to explore potential sites along the banks of northern rivers. The trade in tusks was about  $85 \text{ t yr}^{-1}$  in 2010 (Farah & Boyce, 2019). This mining is unmanaged and mostly illegal (Farah & Boyce, 2019).

The Anti-Atlas Mountains of southern Morocco is the center of a worldwide trade in Paleozoic fossils valued at approximately 40 million dollars per year (Gutiérrez-Marco & García-Bellido, 2018). The enterprise, involving mining and sample preparation, employs approximately 60,000 people (Gutiérrez-Marco & García-Bellido, 2018). Elsewhere, valuable Mesozoic fossils are mined illegally in China and Brazil (Sookias et al., 2013). In China, collectors prize mammals and feathered dinosaurs, and in northwestern Brazil, sites are famous for their fossilized insects, fish, turtles, etc. (Lane, 2011; Sookias et al., 2013).

Mining of sulfur from an active fumarolic vent of a volcano on East Java, Indonesia, is among the most dangerous and arduous ASM jobs. As molten sulfur solidifies, miners work around a fog of hydrogen

sulfide and sulfur dioxide gases to collect sulfur-bearing minerals (Lane, 2011). They carry 90 km loads up out of the volcano and down the mountain. Health problems include skin burns, a variety of lung and respiratory issues, and sometimes death directly from gas exposure (Lane, 2011).

### 3.3. Gold and the Mercury Problem

Not much has changed with ASM for gold and refining processes for hundreds of years, even millennia. Panning or sluicing of placer sands yields gold mixed with other materials. The situation is similar for lode gold. Chunks of rock are broken with hammers in preparation for further crushing in ball mills. Liquid mercury provides a simple way to concentrate gold from a larger volume of finely crushed rock or sediments (UNEP, 2012). Mixing or stirring mercury in the sediments forms a gold amalgam, that is, gold dissolved in mercury, which with additional processing yields purified gold. Other materials are left behind with gold concentrated in the mercury (WHO, 2016). The final step in processing involves heating the mercury-gold mixture to volatilize the mercury, creating a highly mobile and toxic vector of mercury exposure and leaving behind a purified form of gold (WHO, 2016).

The disposal of processed rock and sediments containing residual mercury or volatilization from heating of the amalgam releases mercury to the atmosphere, soils, and aquatic systems, creating enormous and persistent environmental and health impacts (AMAP/UNEP, 2013). Of the many anthropogenic emissions of mercury to the atmosphere, ASM now is the largest source (as of 2013), comprising approximately 37% of total mercury releases (AMAP/UNEP, 2013).

Like other metals, released mercury does not degrade like other contaminants, such as nutrients and most organic compounds. It continues to cycle in the environment and requires centuries to become sequestered in deep ocean sediments (AMAP/UNEP, 2013). For example, the California Gold Rush that began in the northern Sierra Nevada Mountains of the United States in the 1800s featured hydraulic mining for placer gold and mercury for processing. Impacts associated with the careless use and disposal of mercury there remain evident today (Nakamura et al., 2018).

## 4. Health Impacts

There are serious health effects associated with ASM, which are known in general but not in detail. The data problem with ASM extends to health impacts because such mining is often illegal and located in remote, sometimes violent or conflict areas. Moreover, ASM often occurs in the world's poorest countries, which are underserved medically and institutionally, particularly in rural areas.

Our review of ASM and health is designed in a framework similar to that utilized by Stewart (2020). Beyond the obvious occupational hazards, Stewart has developed a more holistic view emphasizing environmental, human, and societal factors as determinants of health (Table 2). Not surprisingly, the economically disadvantaged and untrained work force is at high risk for occupational health effects (Table 2). Chemical exposure is the first major class of hazard. With gold, the latter stages in processing can lead to the inhalation of elemental mercury and exposure to a variety of harmful mineral dusts. There is a long list of severe health effects associated with airways and lungs, neural and behavioral problems, and other body systems (WHO, 2016). Other exposures involve cyanide used in secondary processing and toxic gases (e.g., H<sub>2</sub>S and carbon monoxide) (WHO, 2016).

Burki (2019) considers silicosis from dust inhalation to be the greatest health risk. Small particles of crystalline quartz (silica) and other aluminosilicate minerals in the lungs, bronchia, and trachea lead to scarring and nodular lesions, which impair lung and respiratory function (Leung et al., 2012). Beyond possible lung cancer, silicosis increases the risk of tuberculosis by a factor of 3 (Cowie, 1994), as well as pneumonia and other lung maladies.

The absence of mechanization, long working hours, and extremely hazardous workplaces create biomechanical problems, caused by accidents, lifting, lugging, digging, and falling (Table 2). The associated health impacts include musculoskeletal disorders, overexertion, and trauma (WHO, 2016). Other concerning problems include hearing loss from noise, heat stroke due to extreme temperature and humidity, and death from a variety of workplace accidents.

**Table 2**  
*Determinants of Health, Occupational, Environmental, and Human/Social Factors, Give Rise to Hazards and a Variety of Health Impacts*

Determinants of health	Hazard/risk	Associated health impacts
Occupational	i. Chemical exposures	various; related to elevated mercury, cyanide, methane, dihydrogen sulfide, and carbon monoxide
	ii. Dust inhalation	silicosis, tuberculosis, lung cancer
	iii. Heavy lifting, lugging, digging, falling	musculoskeletal disorders, overexertion, trauma
	iv. Others	hearing, heat stroke, death from mine cave-in, flooding, asphyxiation, and drowning
Environmental	v. Personal characteristics	various; related to pregnant women and children
	vi. Incidental chemical exposure	various; depending upon extent of lead, methylmercury, cadmium, and other metal accumulation
	vii. Mining-related, small, water bodies	mosquito-borne diseases, for example, malaria and dengue fever
Human and social	viii. Poor sanitation	diarrheal diseases, for example, cholera
	ix. Lifestyle/occupation interaction	sexually transmitted infections, comorbidities—silicosis, HIV, and tuberculosis
	x. Inadequate social network, chronic stress	psychological distress, anxiety, depression, sleep loss, impaired immunity, triggering other problems
	xi. Poverty	malnutrition, magnification of disease impacts due to poor housing and absent medical health services
	xii. Violence, wars	various physical and mental problems, death

Next are the environmental determinants of health (Table 2) beginning with “personal characteristics, such as age and sex.” Pregnant women and young children are especially susceptible populations, often severely impacted by harsh environmental settings (Stewart, 2020). For example, processing of gold with mercury may take place in kitchens, leading to risks of inhalation exposures for pregnant women and children (Basu et al., 2015).

An ASM gold mining-related incident in Nigeria illustrates the susceptibility of children to chemical exposures. More than 400 children <5 yr old died of lead poisoning with 1,500–2,000 others needing treatment (Plumlee et al., 2013). This case is unique because an accessory mineral associated with gold mined from a lode deposit, PbS, weathered to a more bioaccessible form. Older children helped with processing, breaking and grinding rock brought to villages. Younger children were at risk for exposures to lead-contaminated dust by ingestion or swallowing dust cleared from the respiratory tract (Plumlee et al., 2013).

This case in Nigeria is also an example of the hazards associated with incidental chemical exposure (Table 2, vi). This category mostly represents nonoccupational exposures to mercury away from mining sites. For example, careless disposal of mercury could lead to contamination of fish with methylmercury. This form of mercury biotransforms and bioaccumulates in marine and freshwater food chains (WHO, 2016). When humans eat contaminated seafood, methylmercury moves from the gastrointestinal tract into the blood stream and eventually to the brain. Neurologic symptoms might range from tingling in the extremities and visual and hearing impairment to muscle tremors, paralysis, and death (WHO, 2016). Because methylmercury affects motor and neural development in a fetus, newborns can suffer from a variety of severe associated problems (WHO, 2016).

Land surface modifications due to aggressive placer mining (Table 2, vii) often produce small water bodies. The concern is that the unintended creation of mosquito habitat may increase the prevalence of infectious diseases such as malaria (Yelpaala & Ali, 2005) and dengue (WHO, 2016). Quite simply, “alluvial gold mining promotes the transmission cycle of the malaria agents” (Villar & Schaeffer, 2019). There are two factors at work: first, the continued presence of humans able to serve as reservoirs, and second,



haphazard digging, creating favorable mosquito habitat (Villar & Schaeffer, 2019). In communities with ASM, there is frequently poor sanitation (Table 2, viii) with the potential to contaminate otherwise fresh-water supplies (WHO, 2016). The result is a rapid expansion of diarrheal diseases, like cholera, which are associated with sewage-contaminated water and food prepared with poor hygiene.

Next on Table 2 are the human and social determinants of health. Lifestyle/occupational interactions (Table 2, ix) lead to an unholy trinity of diseases, like silicosis, HIV, and tuberculosis (Corbett et al., 2000). Anecdotal information points to increases in sexually transmitted diseases as well. Problems of psychological distress (Table 2, x) are rooted in inadequacies in social networks (Stewart, 2020). Similarly, chronic stress contributes to anxiety, depression, etc., along with weakened immunity. Stress also results in cardiac problems and diseases and contributes to atherosclerosis, obesity, and diabetes (Stewart, 2020).

The last two items, poverty (xi) and violence (xii) (Table 2), are little discussed in an ASM context. Yet, poverty and violence are important and nearly omnipresent hazards. Thus, in an upcoming section, we review the health implications of poverty. Our companion paper focuses on violence and child labor.

#### 4.1. A Glimpse of Unhealthy Conditions in ASM

A curtain of corruption and violence hides the true health effects. ASM commonly occurs in remote, desolate, and dangerous places and increasingly, under the influence of foreign actors. However, special circumstances in French Guiana provide an opportunity to peek behind this curtain to obtain the general information reported in Table 2. French Guiana is an overseas territory of France located on the Atlantic coast of South America. Approximately 10,000 (or more) undocumented artisanal miners, mostly Brazilians, are there mining gold (Douine et al., 2018; Egmann et al., 2018). Being a French territory, it has a reasonably well-developed emergency medical system that serves patients in remote, forested areas by helicopter (Egmann et al., 2018). Universities and hospitals there conduct clinical research, funded by European programs (Douine et al., 2018).

Douine et al. (2018) conducted medical evaluations of 421 adults nearby actual mine sites. Of these patients, 297 men worked as miners, and 124 worked as housewives or cooks. The top four medical issues attributed to the mine site were malaria, leishmaniasis, dengue/chikungunya, and intestinal disorders. Malaria and leishmaniasis are parasitic diseases caused by the bites of mosquitoes and sandflies, respectively. Dengue and chikungunya are viral mosquito-borne diseases. The intestinal disorders reflect contaminated water related to poor sanitation. About one third of miners suffered from high blood pressure. Surprisingly, occupational health problems are relatively less frequent according to their assessment.

The study by Egmann et al. (2018) examines responses to medical emergencies in gold mining areas of French Guiana by medical teams dispatched by helicopter. Over two 3 yr periods, 1998–2000 and 2008–2010, there were 340 emergency runs. Illnesses represented 48% of causes; trauma was 44%; and “other” was 8%. In the illness category, infectious diseases, for example, malaria, dengue, zika, and gastrointestinal issues, predominated. The trauma runs contained an interesting collection of problems not obviously associated with mining, including weapon wounds, motor vehicle accidents, burns, and a category of unspecified problems. These studies, however, do not include less acute and more pervasive problems, for example, associated with mental health, substance use/abuse, or sexually transmitted diseases.

These cases illustrate the relative importance of environmental and human and social drivers of health. The drivers will vary from place to place, as a function of the climatic setting, type of mining, and levels of violence. Yet, there are evident commonalities. For example, Villar and Schaeffer (2019) reviewed the occurrence of malaria across Latin America, which found gold mining linked directly to “the direct spread and maintenance of malaria in endemic areas.” With placer mining, malaria transmission by mosquitoes is due to the presence of a population of infected miners and stagnant water bodies created by mining (Villar & Schaeffer, 2019). Countries they mention include Peru (Sanchez et al., 2017), Brazil (Ferreira et al., 2012), French Guiana (Pommier de Santi et al., 2016), and Colombia (Castellanos et al., 2016).

ASM produces spikes in diseases associated with mosquitoes, contaminated water, and food, lack of immunity, and poverty-related issues. In northern Brazil near Venezuela, an influx of approximately 40,000 placer gold ASM miners in the 1990s severely affected the indigenous Yanomami Indians (Villar & Schaeffer, 2019).

Their population declined by approximately 20% in 7 yr due mainly to malaria, but also influenza, tuberculosis, and sexually transmitted diseases (Veecken, 1993; Villar & Schaeffer, 2019).

#### 4.2. Health Impacts Associated With Poverty

Artisan miners are commonly poverty-stricken people that live in poor countries (Musah-Surugu Justice et al., 2017). They become artisanal miners because of personal hardships (Hilson & Garforth, 2012) that require a consideration of other alternatives. For example, in Sub-Saharan Africa, most poor people live in rural areas, working as subsistence farmers on relatively small plots of less than ideal land (e.g., arid to semi-arid settings with poorly developed soils and agricultural infrastructure). The growing inability to create income from farming has led to widespread “agricultural poverty” requiring augmentation of farm incomes. Thus, farmers might enter artisanal mining on a seasonal basis, as a supplemental job, or permanently (Hilson, 2012; Hilson & Garforth, 2012). In some places, ASM has eclipsed farming as the primary source of rural income (Hilson & Garforth, 2012).

In other places, the story might be different. For example, in parts of Peru, Colombia, or Mali, ASM could be a long-standing, slowly changing traditional practice (World Bank, 2009) or involve small teams of more professional opportunists. Increasingly, there are commodity rushes, which can bring tens of thousands of miners to “wild” frontier towns in the jungles of coastal Madagascar or the dry deserts of northern Niger (World Bank, 2009). Besides attracting poor people to nearby mining locales, there are itinerant miners who travel from one boomtown to the next.

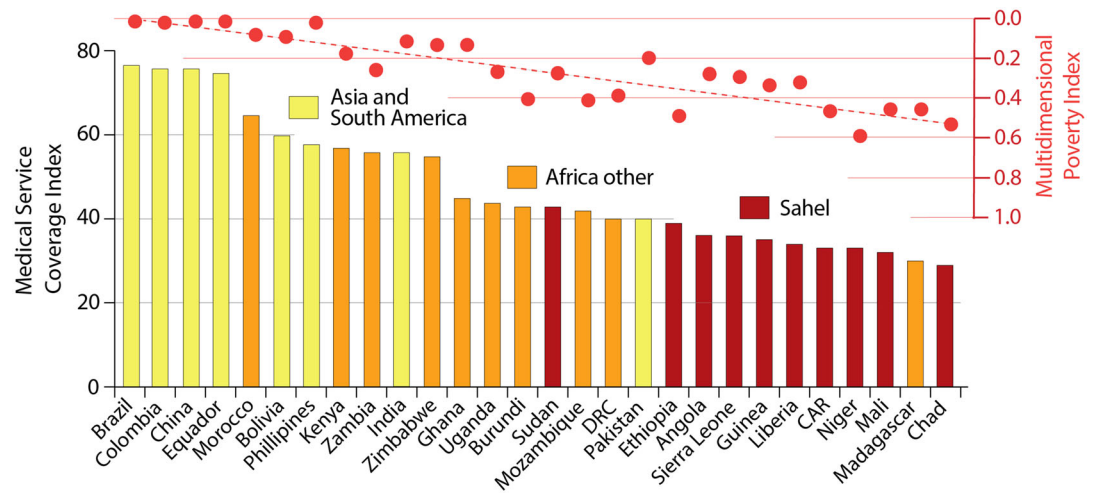
Whatever their reason for being there, ASM provides paying work in areas typically devoid of other employment prospects. Beyond being physically capable, there are no other training or educational requirements. Yet for most, ASM simply trades one poor, subsistence lifestyle for another. The organization of artisanal mining sites precludes an individual “striking it rich.” For example, in Africa, most workers mining for gold are panners, who lack capacity to produce more than trace quantities of gold consistently. Other miners could work as part of a crew and receive a salary to work for pit owners or others. Those in charge finance mining operations and benefit most financially (Hilson, 2012). In too many places, for example, Colombia, Venezuela, and DRC, crews may work under the ultimate direction of criminal gangs, paramilitary groups, or corrupt government or military actors as indicated in our companion paper.

Hilson (2012) addresses the question of why many people work so long in grueling, menial mining jobs. Poverty traps are an important reason. A poverty trap is defined as the “critical minimum asset threshold below which families are unable to successfully educate their children, build upon their productive assets and move ahead economically over time” (Carter et al., 2007). In other words, survival is all that is possible with the available income. These same traps also exist with farming small plots of land or in working small shops in Sub-Saharan Africa (Hilson, 2012).

Criminality is another factor trapping people in poverty cycles. Miners find it difficult to escape predatory loans created by deceptive recruitment, pay-to-play schemes, and other employer-imposed costs. This practice is more suitably named debt bondage, because there is no possible way to pay off loans. Criminal actors can also use violence to keep miners working. Other predatory actors include traders who pay pennies on the dollar for gold or diamonds.

ASM comes with inherent issues that intensify poverty traps. An acute injury might require loans to cover the exigency. A chronic health issue may impact a worker’s productivity permanently, worsening poverty (Hilson, 2012). Artisanal miners commonly are without exclusive rights to claims. Thus, an increasing number of miners could lead to an overall decline in productivity (Hilson, 2012). Similarly, yield in gold, diamonds, etc. could decline for geological reasons (Hilson, 2012), or miners might lack the capacity to mine to greater depths in the subsurface.

Various economic studies around farming in Sub-Saharan Africa suggest that ultrapoor people do not escape rural poverty traps (Hilson, 2012). For the reasons discussed above, we expect the situation for ASM to continue to be worse. Unlike subsistence farming, mining of valuable commodities does create amazing prosperity for a few people. However, those few are typically not the artisanal miners themselves, nor are they typical citizens in countries where those mines are located. In South America and Sub-Saharan Africa, the lucrative rewards from ASM benefit smugglers, criminal gangs, paramilitary groups, revolutionaries, and corrupt elites of the military or government.



**Figure 2.** The medical services coverage index reflects inadequacies in coverage across the Sahel of Africa. The main driver is poverty within countries, as indicated by the multidimensional poverty index.

### 4.3. Being Poor in Poor Countries

Occupational health issues could drive an artisanal miner deeper into poverty. Not so obvious are health impacts with poverty as its cause, which can produce a similar result within communities of artisanal miners. Goodman and Conway (2016) provide examples of how “poverty collides with health.” Impoverished adults have shorter lifespans with a susceptibility toward serious chronic diseases (e.g., diabetes and cancer) related to poor nutrition. Endocrine disruption, as an outcome of living in stressful environments, contributes to cardiovascular diseases and stroke.

Children growing up poor are also at risk (Goodman & Conway, 2016). Absent early and continuing enrichment in a child’s life can impair neurological development. Similarly, adversity and stress related to poverty (e.g., turmoil and violence) have impacts, particularly damaging the “capacity of the brain to develop optimally” (Goodman & Conway, 2016).

The poor in developing countries experience greater problems. For example, in the Sahel of Africa, children suffer from undernutrition (Osgood-Zimmerman et al., 2018). This problem leads to growth stunting, wasting, and to being underweight. Associated neural problems can begin before birth from maternal malnutrition and continue during a child’s early development due to vitamin deficiencies (Kerac et al., 2014). Cyclically, “poverty leads to ill health and ill health leads to poverty” (Wagstaff, 2002).

Another serious problem with poverty is limited access to medical care. Many people end up extremely ill or dying from treatable diseases like malaria, diarrhea, and pneumonia (O’Donnell, 2007); children often have a serious risk of death (O’Donnell, 2007). Almost all the health impacts in Table 2 are magnified without access to preventative care or early treatments.

Poor people in poor countries also have the greatest difficulties in accessing medical care (Peters et al., 2008). To illustrate the national disparities in health services, we summarize service coverage data (WHO, 2017) for 28 countries associated with the largest populations of artisanal gold miners (Figure 2). Twenty of these countries are located in Africa, including eight in and around the Sahel. The remaining countries are in South America and Asia. The service coverage index, ranging from 0–100, represents both the capabilities of facilities (e.g., capacity, staff, and medicines) and coverage of basic specialties in infectious diseases, non-communicable diseases, and family practice (WHO, 2017). Indices for service coverage are lowest for Africa and uniquely low for the Sahel (Figure 2). Index values are higher for countries in South America and Asia. For comparison, developed countries have values >80 (WHO, 2017).

Poverty in countries correlates with service coverage data. We plot an index of multidimensional poverty (0–1) for each of the countries and a trend line. This index is the product of multiplying the intensity of deprivation in a country by the fraction of the population with a deprivation equal or >33%

(UNDP, 2019). For example, with Chad the intensity of deprivation (0.623) is multiplied by the head count (0.857), giving 0.533, the multidimensional poverty index. Clearly, service coverage is worse for poor countries, especially those in or around the Sahel. Because these two indices represent national values, they do not reflect the heterogeneity within a country. In the poorer countries, most medical services are available in major and mostly more prosperous cities. Commonly, those places with ASM activities are vastly underserved.

Another critical factor affecting access to care is affordability (Peters et al., 2008). All costs for care, treatments, travel, food, and accommodations are out of pocket, deterring the poor from treatments (Peters et al., 2008). Borrowing money for medical treatments represents an economic shock that moves families even deeper into poverty from which they often cannot recover (Hilson, 2012).

## 5. Concluding Comments

It is difficult to develop a clear picture of ASM. First, the industry is broad with a disproportionate focus on the most valuable commodities, 3TG, diamonds, and precious stones. Funding of what studies there are has come from large companies using this information to elucidate possible problems in their commodity supply chains (e.g., blood diamonds and child labor) or from governments trying to investigate relationships with organized crime or foreign actors. Studies by World Bank have been influential as part of their long-term efforts to assist developing countries economically. There is much less interest in studies around the more common commodities, such as rock aggregates, coal, or other precious metals (e.g., rare earth elements). Exceptions include a smaller number of nongovernmental organizations (NGOs) and news organizations looking to illuminate environmental and human-rights abuses. As the price of valuable commodities increase, the industry is increasingly attractive to criminal enterprises to diversify outside of their usual areas of commerce. Fragile states are especially at risk because they have little capacity to govern, poor medical systems, and elites who sometimes participate financially.

Second, ASM is spread out geographically and different in detail from place to place. Papers and studies often focus on local or regional areas on eclectic topics of interest, but with minimal exposure to mining sites. This geographic diversity makes it logistically difficult for academics and others to get around. The even greater difficulty—the third issue—is that data largely do not exist and likely never will. Poor countries have little capacity or incentive to manage and collect information related to ASM; simply put, they lack long-term strategic planning initiatives that consider the environmental or economic costs of the legacy left by ASM. The illegal actors organizing and profiting from ASM have no interest in illuminating their operations and value chains. Just the opposite, we expect aggressive resistance to investigative studies.

ASM sometimes provides an opportunity to diversify income in the face of a decline in subsistence agriculture (Bryceson, 2002). Yet, for most, ASM often trades one kind of generational poverty for another, while bearing a burden of health risks and the turmoil associated with work in an informal cash-rich business. The associated health impacts are largely unknowable. The usual repositories of medical information, patient health records, public health surveys, etc., simply do not exist. Health assessments are largely inferential, based on extrapolation from poor populations of developed countries.

A particular problem around ASM is studying a collection of problems that defy the usual investigative strategies. There is little likelihood that the data problems could get better any time soon, and there are reasons to expect that problems could get worse. Thus, progress in research will require innovation, for example, with the development of proxy data sets to understand ASM better and theoretical approaches to address health problems. There has been useful progress in both directions. For example, researchers at the U.S. Geological Survey demonstrated the potential of remote sensing and geological modeling techniques for quantitatively monitoring ASM activities in Côte d'Ivoire and Guinea, respectively (Chirico et al., 2014; Chirico & Malpeli, 2013). Their analyses filled in significant gaps in knowledge concerning diamond production in both countries and identified shifts in production capacity from one region to another in Guinea. The study of sand mining in Poyang Lake (de Leeuw et al., 2010) also showed the potential of remote sensing in estimating the extent of sand mining by counting barges.

Health studies have many of the same data problems already discussed. Difficulties are magnified by the general absence of medical facilities in poor countries and specific difficulties of isolated mine sites and medical research in dangerous settings. However, studies in French Guiana (Douine et al., 2018;



Egmann et al., 2018) point to the likely existence of other unique collections of public health data relevant to ASM to be discovered and exploited. Another potential direction is in modeling risk and prevalence of diseases, such as malaria, leishmaniasis, dengue, and chikungunya as a function of landscape alteration with placer mining. These approaches involve remote sensing, environmental databases, and statistical modeling. A pertinent collection of work exists for the Amazon River basin with studies, for example, on malaria risk as a function of deforestation (de Oliveira Padilha et al., 2019), malaria spread associated with frontier expansion with different types of work activities, including ASM (Souza et al., 2019), and on relationships between forest clearing and malaria, which includes feedbacks from actual malaria burdens (MacDonald & Mordecai, 2019). The methods would require downscaling for ASM settings but hold promise.

The academic view of ASM largely assumes that governments have an interest and capacity to transform their agencies in a way to have these mining activities benefit their nations economically. However, the wealth associated with the development of natural resources flows along legal and illegal supply chains to countries able to add value to the resource or to criminal actors with the capacity to manage mining through intimidation, violence, and payoffs.

### Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

### Data Availability Statement

Figure 1 is public domain and available on the website of the United States Geological Survey ([https://www.usgs.gov/centers/fbgc/science/special-geologic-studies-artisanal-and-small-scale-mining-conflict-minerals?qt-science\\_center\\_objects=0#qt-science\\_center\\_objects](https://www.usgs.gov/centers/fbgc/science/special-geologic-studies-artisanal-and-small-scale-mining-conflict-minerals?qt-science_center_objects=0#qt-science_center_objects)). Data on health service coverage and multidimensional poverty both used in Figure 2 can be found in WHO (2017) and UNDP (2019), respectively.

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