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Environmental health of communities in the Lake Atitlán watershed, Guatemala: creating a global model for community-based solutions

Salud ambiental de las comunidades en la cuenca del Lago Atitlán, Guatemala: creando un modelo global para soluciones comunitarias

Frank A. von HIPPEL
Department of Community, Environment & Policy, Mel & Enid Zuckerman College of Public Health, University of Arizona, Tucson, AZ, USA
Correspondence: Frank A. von Hippel (frankvonhippel@arizona.edu)
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Abstract: The Lake Atitlán watershed exemplifies many of the environmental health problems in Guatemala, as well as the potential for community-based solutions. The most important of these problems are poor air and water quality, which impose a substantial public health burden. Several paradigms are useful to contextualize the environmental health of Lake Atitlán, including "developmental origins of health and disease" - DOHaD - (many diseases throughout the lifespan are caused by environmental stressors during development), "endocrine disruption" (alteration of hormone systems due to chemical exposure), and "planetary boundary threats" (anthropogenic impacts that imperil the integrity of life on Earth). Similarly, paradigms for public health solutions provide a way forward. One such paradigm is "One Health" (the concept of simultaneously addressing health at the interface of human, animal, and environmental health), which can facilitate powerful alliances with broadly overlapping goals. Another is "WASH" (water, sanitation, and hygiene), which is an approach to public health focused on clean water, availability of sanitation facilities, and good hygiene practices. Improved public health could be achieved by combining multiple societal assets with a focus on maternal and child health, using principles from One Health and WASH. The Lake Atitlán watershed could serve as a case study for Guatemala that leads to both scaling up local solutions and implementing effective policies at the national level. Solutions should be implemented within the cultural strengths of the K'iche'e, Kaqchikel, and the Tz'utuiil communities, who proudly maintain their languages, customs, and worldview. Relevant resiliencies also include local governance and self-reliance, the cultural importance of water, expertise of universities such as the Universidad del Valle de Guatemala, community-engaged government programs such as those implemented by the Autoridad para el Manejo Sustentable de la Cuenca del Lago de Atitlán y su Entorno, and international partnerships. Ideally, the people in each community will have agency to improve environmental health and will do so through community-engaged research and interventions designed to arrive at the essential destination of clean air and clean water.

Keywords: air quality, DOHaD, endocrine disruption, maternal and child health, One Health, planetary boundary threats, WASH, water quality.

Resumen: La cuenca del lago Atitlán ejemplifica muchos de los problemas de salud ambiental en Guatemala, así como el potencial de las soluciones comunitarias. Los más importantes de estos problemas son la mala calidad del aire y del agua, los cuales representan una carga significativa para la salud pública. Varios paradigmas son útiles para contextualizar la salud ambiental del lago Atitlán, entre ellos los "orígenes del desarrollo de la salud y la enfermedad" (muchas enfermedades a lo largo de la vida son causadas por factores ambientales durante el desarrollo), la "disrupción endocrina" (alteración de los sistemas hormonales debido a la exposición a sustancias químicas), y las "amenazas a los límites planetarios" (impactos antropogénicos que ponen en peligro la integridad de la vida en la Tierra). De manera similar, los paradigmas en salud pública proporcionan una ruta clara para avanzar. Uno de estos paradigmas es el concepto de "Una Sola Salud" (abordaje simultáneo de la intersección entre la salud humana, animal y ambiental), lo cual puede facilitar alianzas poderosas con objetivos ampliamente coincidentes. Otro es el enfoque "ASH" (agua, saneamiento e higiene), que es una estrategia de salud pública centrada en el acceso a agua limpia, la disponibilidad de instalaciones de saneamiento y la promoción de buenas prácticas de higiene. La mejora de la salud pública podría lograrse mediante la combinación de múltiples recursos sociales, con un enfoque en la salud materna e infantil, utilizando principios de Una Sola Salud y ASH. La cuenca del lago Atitlán podría servir como un modelo/caso de estudio para Guatemala, tanto al escalar soluciones locales como al implementar políticas efectivas a nivel nacional. Las soluciones deben aplicarse respetando, integrando y aprovechando las fortalezas culturales de las comunidades K'iche'e, Kaqchikel y Tz'utujil, que mantienen con orgullo sus idiomas, cosmovisión y costumbres. Otras fortalezas también incluyen la gobernanza local y la autosuficiencia, la importancia cultural del agua, la experiencia de universidades como la Universidad del Valle de Guatemala, programas gubernamentales con participación comunitaria como los implementados por la Autoridad para el Manejo Sustentable de la Cuenca del Lago de Atitlán y su Entorno, y las alianzas internacionales. Idealmente, las personas en cada comunidad tendrán la capacidad de actuar para mejorar la salud ambiental, y lo harán mediante investigaciones e intervenciones con participación comunitaria, orientadas a alcanzar el objetivo esencial de tener aire y agua limpios.

Palabras clave: Amenazas a los límites planetarios, ASH, calidad del agua, calidad del aire, disrupción endocrina, orígenes del desarrollo de la salud y la enfermedad, salud materna e infantil, Una Sola Salud.

Personal Background in Guatemala

Guatemala's allure first captivated me in 1994 when my wife and I were both graduate students. At the time, inexpensive student tickets were available in student travel offices. We visited the Berkeley agent and asked for the least expensive tickets they had to Latin America, which turned out to be flights to Ecuador. As we purchased the tickets, the travel agent told us we could have a free stopover in Central America, and on a whim, we chose Guatemala.

We knew little about Guatemala, except that it was still in the midst (at the tail end) of a long civil war. When we arrived at the airport in Guatemala City, soldiers handed us a flier that specified where we could safely go (a few places) and where to avoid (most of the country). Ever since that visit, we have been hooked on Guatemala and visited many times, throughout the country, often with our children, who even attended an elementary school in Antigua during one of our extended stays to learn Spanish.

What is it about Guatemala that sparked our intense interest and warm feelings? The people: Guatemala is one of the friendliest countries, with a diverse cultural composition that varies from town to town in its food, language, clothing, customs, and coffee. It may be the best place to learn Spanish, facilitated by the welcoming nature of Guatemalans, who appreciate foreigners speaking with them in Spanish - even when they are just learning to do so. And Guatemala has a fascinating history with a rich heritage extending from the Mayan empire to the Spanish colonial period, to its modern melding of indigenous and Ladino cultures.

On one of these many trips to Guatemala, in 2013, Alberto Rivera Gutiérrez, the owner of Reserva Natural Atitlán, introduced me to a team of researchers who were investigating the eutrophication of Lake Atitlán. The lead investigators were Eliska Rejmánková from the University of California, Davis, and Sudeep Chandra from the University of Nevada, Reno. We met at the field station in Santa Catarina Polopó, operated by Amigos del Lago de Atitlán (Amigos). It turned out that the team lacked an ecotoxicologist. Given the potential importance of chemical pollution entering the lake from the surrounding watershed, I joined the research endeavor and have done research in Guatemala most years since.

One of the most rewarding things I did immediately after joining the team was to help teach environmental sampling techniques and aquatic ecology to Guatemalan students on a project funded by USAID. Although USAID funding for this program soon lapsed (and then a decade later the second Trump Administration eviscerated USAID), many Guatemalans who took our course went on to become environmental professionals who make important contributions to Guatemala's environmental agencies, universities, and NGOs. Some of them are now collaborators in our ongoing research projects. This anecdote speaks to the importance of capacity building and of agencies such as USAID, which will need to be rebuilt or replaced. It also brings me to another highlight of my experiences in Guatemala: the ease with which I have been able to collaborate with Guatemalans at institutions such as Amigos, la Universidad del Valle de Guatemala (UVG), la Autoridad para el Manejo Sustentable de la Cuenca del Lago de Atitlán y su Entorno (AMSCLAE), the Center for Studies of Sensory Impairment, Aging and Metabolism (CeSSIAM), community health clinics throughout the Atitlán watershed, and others. This hunger for productive collaboration is an important asset for Guatemala's future.

Exposure Science and Risk Assessment

Lake Atitlán sits in a collapse caldera of the volcanic highlands of western Guatemala (Newhall 1987). The lake holds special status in Guatemala due to its size (the largest by volume in Guatemala at 24 km^3), depth (the deepest in Central America with a maximum depth of 341 m and a mean depth of 183 m), and cultural and economic significance for the ~400,000 mostly indigenous people who live in its watershed (Rejmánková *et al.* 2011, Flores-Anderson *et al*. 2020; Neher et al. 2021). The drainage area into the lake comprises 414 km^2 (Farráns *et al.* 2018). The lake is fed by the San Francisco and Quiscab rivers, but it lacks a surface discharge outlet, leading to an unusually long hydraulic retention time of 80 years (Neher *et al.* 2021). Hence, inputs of pollutants to the lake are not diminished by surface outflows.

Although the lake is naturally oligotrophic, the constant inputs of fertilizers and sewage have shifted the lake to a more eutrophic state, which has led to cyanobacteria blooms (first reported in 2008) and depletion of dissolved oxygen (Fig. 1) (Rejmánková *et al*. 2011; Neher *et al*. 2021). Cyanobacteria can produce cyanotoxins, which, at high enough concentrations, pose a risk to human health through consumption of contaminated water and animals (Rejmánková *et al*. 2011). Reduced dissolved oxygen harms, and can eventually extinguish, aquatic animal populations, including important subsistence species for the Atitlán communities. Therefore, eutrophication also exacerbates food insecurity.

My first Guatemalan graduate student, Hugo Villavicencio, investigated the trophic ecology and concentrations of toxic metals and metalloids in Atitlán's populations of fishes, crabs, and snails (Villavicencio 2019). These are the kind of data that allow researchers to conduct quantitative risk assessments for public health endpoints such as cancer. Toxic metals, such as mercury and lead, and metalloids, such as arsenic, have both natural (e.g., volcanoes) and anthropogenic sources. In the Atitlán watershed, anthropogenic sources of these toxic elements

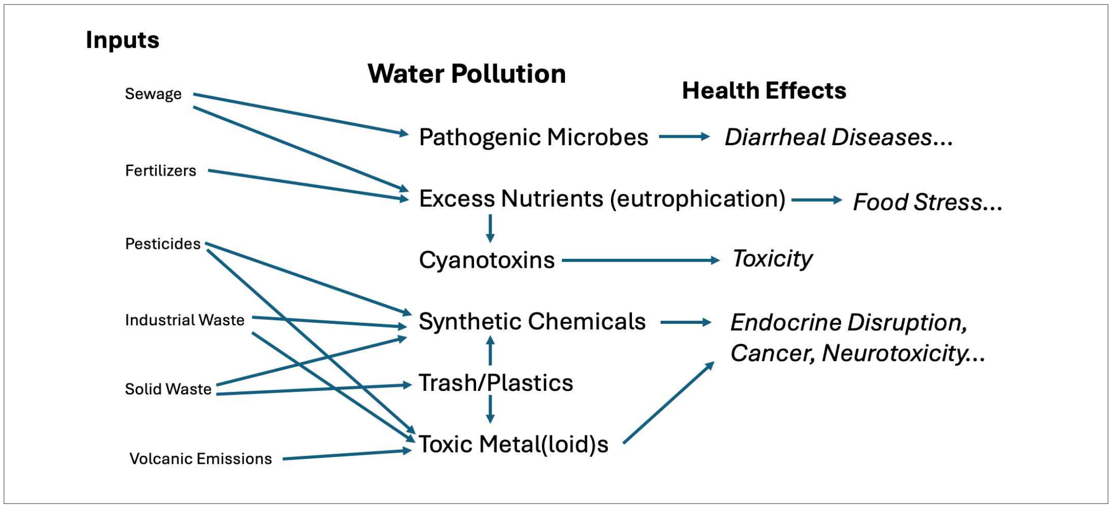

Figure 1. Schematic representation of pollution inputs to Lake Atitlán, and examples of resulting risks to human health.
Figura 1. *Representación esquemática de las fuentes de contaminación en el Lago Atitlán y ejemplos de los riesgos resultantes para la salud humana.*

include pesticides (e.g., fungicides and insecticides) and products used in urban and small industrial settings (Fig. 1).

But toxic metal(loid)s are only a small part of the chemical pollution of Lake Atitlán. The lands surrounding the lake are used extensively for agriculture, including both monocultures for cash crops and small land holdings for subsistence crops (Neher *et al.* 2021). Both rely on extensive use of pesticides and fertilizers. Pesticides, comprising hundreds of chemicals from many chemical classes, including banned or restricted compounds such as organochlorine insecticides (von Hippel 2020), accumulate in the lake and its organisms. Industrial chemicals, chemicals derived from household and personal care products, and microplastics also accumulate in the lake and its organisms (Dix & Romero 2020). Trash improperly disposed and trash burning also contribute an unknown chemical burden to the lake (Dix & Romero 2020; Neher *et al.* 2021).

Environmental Health Concerns in Guatemala

In the 1950s and 1960s, pollution in the United States had impacted the environment to such an extent that rivers caught on fire and cities such as Los Angeles had smog alerts more often than not. This assault on the environment and consequent degradation of public health led to pressure for the passage of seminal environmental legislation in the 1960s and early 1970s, such as the Clean Air Act, Clean Water Act, and Safe Drinking Water Act. These acts and other environmental legislation led to large improvements in environmental quality, including, for example, near universal safe drinking water throughout the U.S.

Guatemala's situation is similar to that of the U.S. prior to the implementation of these measures, but with additional and substantial pressures that the U.S. never faced. Guatemala has the fastest growing population in Central America, and ~59% of the population lives in poverty, with 40% of the indigenous population living in extreme poverty (Neher *et al.* 2021). In the Atitlán watershed, 70% of the population lives in poverty (Farráns *et al.* 2018). As in many other parts of Guatemala, the combination of a rapidly growing population and poverty have led to the common outcome of untreated or poorly treated sewage entering the drinking water supply (the lake) and contaminating the drinking water with pathogenic microbes (Neher *et al.* 2021). An estimated 45,500 m^3 of sewage is produced daily in the Atitlán watershed, of which 80% is untreated and the remainder is treated at levels that do not meet Guatemalan regulations (Farráns *et al.* 2018). The lack of clean public drinking water imposes a substantial public health burden on Atitlán communities (Farráns *et al.* 2018) (as it does elsewhere in Guatemala), and leads to the otherwise unnecessary expense and associated plastic pollution of bottled water. Similarly, Guatemala's growing population and lack of environmental controls have led to terrible air pollution, which creates a burden of diseases that damages public health and economic development. Thus, clean water and clean air are the foremost goals of effective policies and actions to improve public health.

Community resources such as Lake Atitlán often suffer degradation due to the "tragedy of the commons" (Hardin 1968) - that is, when people extract benefits from a communal resource, they will tend to overuse it and even destroy it as they race to benefit from the resource before others can outcompete them. Overfishing is a classic example of this problem. But this tragedy can also be extended to ecosystem services. Lake Atitlán, due to its size, provided safe drinking water and abundant food resources for thousands of years, but it can no longer sustain these services due to the population growth in the watershed. For example, sewage inputs now outstrip natural degradation processes, and the water is no longer safe to drink.

Paradigms for an Improved Understanding of Public Health Needs in Guatemala

Developmental Origins of Health and Disease. Many diseases throughout the lifespan are caused by environmental stressors during development, a concept known as "developmental origins of health and disease", or DOHaD (Heindel & Vandenberg 2015). These stressors may include poor nutrition, infections, and chemical exposures, with later-onset health problems ranging from cancer to obesity to infertility to neurological disorders (Painter *et al.* 2005; Barker 2007; Heindel & Vandenberg 2015). Adverse health outcomes of developmental exposures are often mediated by altered epigenetics, which can lead to transgenerational effects (Heindel & Vandenberg 2015). Effects depend on the timing of exposure relative to sensitive windows of development as different systems are forming at different times, such as during a particular trimester or post-natally (Heindel & Vandenberg 2015). The latency between an exposure and adverse outcome can range from months to decades, leading to difficulty attributing causality in human studies (Heindel & Vandenberg 2015). The timing, severity, and incidence of diseases can all be affected by early developmental exposures, and effects often vary by sex and genetics (Heindel & Vandenberg 2015). These early developmental stressors often lead to permanent effects, or so-called organizational effects, due to the changes that are induced in tissues and organs that are plastic early in development and then take on their permanent structures (as opposed to activational effects that occur after development is complete, which are reversible). For example, the development of infertility due to chemical exposure in the womb is an organizational effect, whereas chemical-induced hypothyroidism in an adult that resolves upon termination of the exposure is an activational effect.

Endocrine Disruption. An important pathway of DOHaD is alteration of hormone systems due to chemical exposure. Chemicals may disrupt any part of the life cycle of a hormone, including synthesis, storage, transportation in the blood, binding to a receptor, post-binding action, and degradation, and this disruption may occur through many mechanisms (La Merrill *et al.* 2020). For example, estrogenic effects, which are commonly induced by synthetic chemicals, can profoundly alter development and lead to outcomes ranging from undescended testes in babies to estrogen-mediated cancers in adults (La Merrill *et al.* 2020).

Planetary Boundary Threats. We can perhaps better understand the environmental health of Lake Atitlán by putting the issues in the context of planetary boundary threats, which define anthropogenic impacts that imperil the integrity of life on Earth (Persson *et al.* 2022). For example, approximately half of the Earth's terrestrial surface has been converted from natural to human altered habitats (Riggio *et al.* 2020), and this land use/land cover change is the number one cause of extinction (Wilcove *et al.* 1998). In the paradigm of planetary boundary threats, this is known as land-system change. We can use this as a starting point in a simplified model of the environmental health of Lake Atitlán (Fig. 2).

Paradigms for Public Health Solutions

One Health. "One Health", or "Una Sola Salud", is the concept of simultaneously addressing health at the interface of human, animal, and environmental health (Fig. 3) (Lebov *et al.* 2017). The need for this is obvious for zoonotic diseases (infections that are transmitted between animals and humans) as these cannot be adequately combatted without understanding the ecological conditions (e.g., a warming climate allows insect vectors of disease to expand their range to higher latitudes), the vectors and animal reservoirs (both domestic and wild), and the ecology of the interface of infection between humans and animals (Ghai *et al.* 2022). Similarly, pollution problems can be understood and addressed more comprehensively by employing the One Health framework.

Chemical and biological pollutants in Lake Atitlán do not only affect human health; the health of aquatic animals is also impacted, which in turn further undermines human health. Pollution leads to the diminution, and sometimes the extirpation, of animal populations, which increases food stress for people who rely on those animals. Animals that survive in a polluted environment will have elevated concentrations of pathogens, toxins, and synthetic chemicals that are transmitted to the people who eat them. Clearly, the health of the aquatic environment and its animal populations need to be addressed simultaneously with the human health concerns. This need can create powerful alliances with broadly overlapping goals, such as between environmental groups and public health programs. Even unlikely alliances can be forged through One Health, such as combining the interests of business groups that rely on a healthy tourism economy with environmental groups promoting conservation. Therefore, the One Health concept demonstrates that interest groups that might otherwise compete for resources can benefit through collaboration. In the case of Lake Atitlán, these collaborations can be facilitated by entities such as AMSCLAE and UVG (e.g., https://www.ces.uvg.edu.gt/page/project/proyecto-una-salud/).

WASH. Water, sanitation, and hygiene (collectively "WASH") is an approach to public health focused on clean water, availability of sanitation facilities, and good hygiene practices. WASH programs for the benefit of global health are integrated into the international programs of major donor countries such as the U.S. (e.g., CDC 2024) as well as international organizations such as the World Health Organization (e.g., WHO 2025). WASH concepts and techniques appropriate for low-resource countries are already being implemented in many parts of Guatemala. However, the communities of the Atitlán

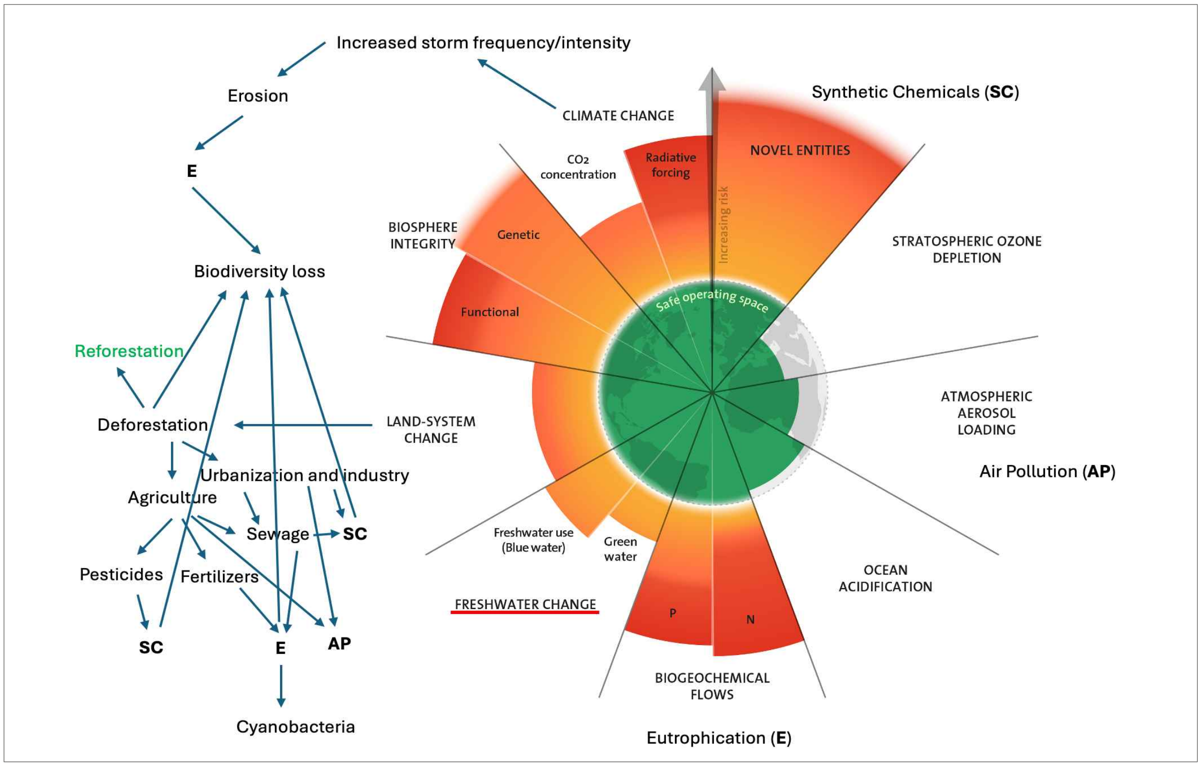

Figure 2. Planetary boundary threats and how they are exemplified in Lake Atitlán. The watershed has experienced high levels of deforestation (*land-system change*) to facilitate the expansion of agriculture and urbanization, which both lead to inputs of biological and chemical contaminants into the lake (*novel entities* in the parlance of planetary boundary threats, and here referred to as synthetic chemicals [**SC**]) and hence *freshwater change* and eutrophication [**E**] (*biogeochemical flows*). These inputs are also tied to biodiversity losses (*biosphere integrity*) and air pollution [**AP**] (*atmospheric aerosol loading*), and effects are exacerbated by *climate change*. Hence, environmental issues in Lake Atitlán exemplify components of seven out of the nine planetary boundary threats (the exceptions being ocean acidification and stratospheric ozone depletion). Modified from Azote for Stockholm Resilience Centre, based on analysis in Richardson *et al.* (2023).

Figura 2 . *Amenazas a los límites planetarios y cómo se ejemplifican en el lago Atitlán. La cuenca ha experimentado altos niveles de deforestación (cambio en el uso de suelo) para facilitar la expansión de la agricultura y la urbanización, lo que conduce a la entrada de contaminantes biológicos y químicos en el lago (entidades nuevas en la terminología de las amenazas a los límites planetarios, y aquí denominadas productos químicos sintéticos [**SC**]), lo que a su vez provoca cambios en el agua dulce y eutrofización [**E**] (flujos biogeoquímicos). Estas entradas también están relacionadas con la pérdida de biodiversidad (integridad de la biosfera) y la contaminación del aire [**AP**] (carga de aerosoles atmosféricos), y sus efectos se ven exacerbados por el cambio climático. Por lo tanto, los problemas ambientales en el lago Atitlán ejemplifican componentes de siete de las nueve amenazas a los límites planetarios (con la excepción de la acidificación oceánica y la disminución del ozono estratosférico). Modificado de Azote para el Stockholm Resilience Centre, basado en el análisis de Richardson* et al. *(2023).*

watershed illustrate the relatively haphazard nature of these programs, as some communities have access to clean drinking water while other communities drink untreated water straight from the lake, and some communities use a mix of both (Dix & Romero 2020). Therefore, the lack of clean water in much of Guatemala is due to a combination of poorly integrated management of water resources nationally and regionally, insufficient wastewater treatment at the municipal level, and poor hygiene at the household level.

WASH programs need to be systematically implemented in Guatemala. Although WASH programs typically demonstrate a massive public health return on investment, their successful implementation in Guatemala faces many hurdles in addition to the financing, such as political infighting over competing programs and educational barriers to implementation. These barriers are likely best overcome through a combination of

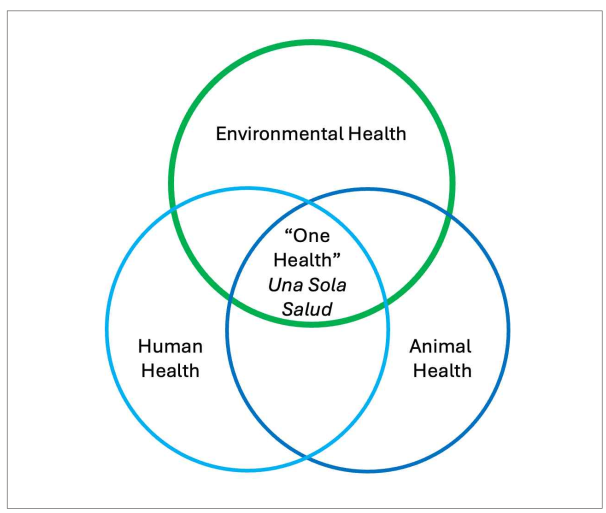

Figure 3. The One Health concept.
Figura 3. *El concepto de "Una Sola Salud".*

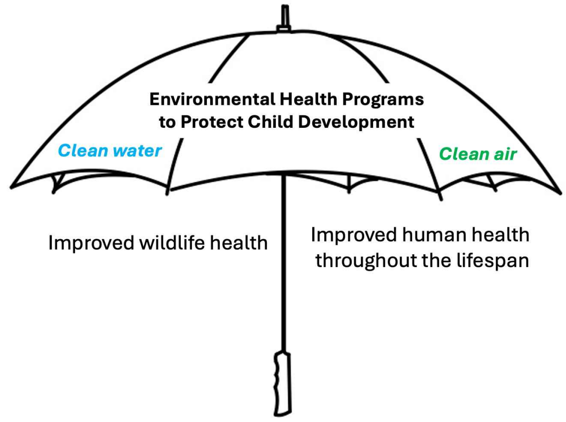

Figure 4. The concept of an "umbrella" species applied to the developing child. Measures that ensure that water and air are sufficiently clean for healthy child development will also be broadly protective of human health through the lifespan and wildlife health.

Figura 4. *El concepto de una especie 'paraguas' aplicado al niño en desarrollo. Las medidas que garantizan que el agua y el aire estén suficientemente limpios para un desarrollo saludable del niño también protegerán de manera amplia la salud humana a lo largo de toda la vida, así como la salud de la vida silvestre.*

national programs by the Guatemalan government coupled with community-centered educational and technical training programs.

Maternal and Child Health

A useful concept in conservation biology is that of the "umbrella species" (Wilcox 1984). If you design a conservation program that protects a vulnerable species (e.g., those of large body size, high trophic position, high metabolic requirements, or patchy distributions) or a keystone species on which the ecosystem depends, then those conservation measures should also protect a large fraction of other species in that ecosystem (Wilcox 1984). For example, measures to protect a top predator such as the mountain lion or a charming but vulnerable species such as the panda bear would also protect many other species in that ecosystem, including those that are not charismatic and hence would otherwise receive little support from the public. In the same way, environmental health programs designed to protect the most vulnerable people (the fetus and the developing child) will also be protective for the health of people across the lifespan, as well as the health of wildlife that is also impacted by pollution (Fig. 4).

Common childhood diseases such as asthma and diarrheal infections are often caused by poor air and water quality, and effective policies to improve air and water quality would improve the health of everyone, not just children. In the same way that political support can be garnered to protect charismatic wildlife, people are especially concerned about the health of their children. For example, the detection of strontium-90 in baby teeth in 1961 raised public alarm about radioactive fallout from atmospheric nuclear weapons testing (Reiss 1961). Similarly, the discovery in the 1960s of DDT in American women's breastmilk at concentrations five times higher than that allowed in cow's milk fueled a backlash against organochlorine pesticides (Graham 1970), and concern about flame-retardant additives led to public policy actions after researchers in the late 1970s pointed out the cancer hazard for children wearing flame-resistant pajamas (Blume & Ames 1977).

An example of how this approach might gain traction for Lake Atitlán is the problem of childhood stunting. Stunting is defined by inadequate growth with a height that is < 2 standard deviations of the WHO child growth standards median (i.e., Z-score=-2.0) (WHO 2015). Stunting happens during the first 1,000 days of life (WHO 2015; Tschida *et al.* 2021) due to poor maternal health and inadequate access to quality nutrition (WHO 2017; Gatica-Domínguez *et al.* 2019). Stunting therefore fits the paradigm of DOHaD.

Guatemala has the highest prevalence of stunting in the Western Hemisphere and the 6th highest globally (MSPAS 2017; Gatica-Domínguez *et al*. 2019; Juarez *et al*. 2021). A collaborative team comprised of researchers from the University of Arizona and CeSSIAM, led by my postdoc Sandra Rodríguez Quintana, examined the possible contributions of toxic metal(loid)s in breastmilk to stunting in Atitlán communities (Rodríguez Quintana *et al*. 2025). We found an association between concentrations of arsenic, barium, beryllium, and lead with stunting of infants in Panajachel and Santiago Atitlán, and the concentrations of arsenic and lead in many of the breastmilk samples in these communities exceeded WHO guidelines. Our results also indicated that drinking water is an important source of toxic elements. Providing safe drinking water would therefore likely reduce the incidence and severity of childhood stunting both by reducing concentrations of toxic metal(loid)s and by decreasing exposure to pathogenic microbes that are responsible for chronic maternal and childhood diseases.

Not only would the provision of clean drinking water reduce childhood stunting, but it would also benefit children's health by lowering the burden of toxic metal(loid)s on cognitive development. Lead provides the classic example as lead exposure induces both irreversible losses of IQ and increases in problematic behavior including violence (Needleman 2000; Nevin 2000, 2007; Needleman *et al.* 2002; Reyes 2007; Fergusson *et al.* 2008; Wright *et al.* 2008; Mielke & Zahran 2012; Boutwell *et al.* 2016; Feigenbaum & Muller 2016). Therefore, measures to provide clean drinking water would have numerous benefits for the development of children, and of course be protective of the health of all Atitlán residents. The political will, community support, and resource allocation to achieve these measures may be more feasible under the banner of child health (Fig. 4).

Ways Forward

How can Guatemala achieve the successes of the U.S. Clean Air Act and Clean Water Act with its lack of resources? The environmental health problems experienced by Guatemala are common throughout the developing world, though Guatemala also has a unique combination of liabilities and assets relevant to the problems. If we view the Atitlán watershed as an exemplar, perhaps the solutions involve scaling up as much as they do legislating down. Municipalities can find water filtration or treatment solutions that are culturally acceptable and effective, perhaps with funding from NGOs and with the expertise of academics. Successful programs at the local level can then be scaled up nationally. This could be facilitated via legislation that rewards communities that provide safe drinking water and other WASH measures. Similarly, air pollution restrictions, such as banning buses that spew particulate pollution, could be implemented locally and rewarded by the national government.

Solutions should be implemented within the cultural strengths of the K'iche'e, Kaqchikel, and the Tz'utuiil communities in the Atitlán watershed, who proudly maintain their languages, customs, and worldview. Relevant resiliencies also include local governance and self-reliance, the cultural importance of water, expertise of universities such as UVG, community-engaged government programs such as those implemented by AMSCLAE, and international partnerships.

Impediments to effective solutions include poverty, population growth, increased consumption, corruption, unstable governance, insufficient education and literacy, and political misalignment. These problems are intertwined. For example, population growth leads to greater poverty, which reduces resources for education. Illiteracy and poor education increase the risk of political misalignment and disagreement as misinformation competes with facts and helpful solutions for political attention. And some assets that promote community cohesion, such as strong cultural practices and indigenous languages, can also impede agreements among communities due to cultural or linguistic misunderstandings, despite the need for cooperation for the good of everyone in the watershed. Furthermore, those who benefit economically from the current situation, such as providers of bottled water, may resist changes that undermine their business raison d'être.

These assets and liabilities therefore must be considered holistically such that all the communities in the watershed feel that they are benefiting from chosen solutions. For example, effective wastewater treatment plants in each community could solve the problem of pathogens entering the lake and thereby greatly improve availability of safe drinking water but would not address the problem of eutrophication. Exporting sewage from the watershed in a pipeline could simultaneously address pathogens and eutrophication, but efforts to follow this route have been stymied by misinformation and considerable backlash. The provision of clean drinking water can best be handled at the municipal level with water treatment plants, but in the absence of that, residents rely on in-home filters. Similar opportunities, impediments, and trade-offs are encountered with other environmental health problems, such as addressing vehicle and industrial emissions.

I am not a Guatemalan, so I am just speculating, but my visits to Guatemala over 30 years have made an impression on me that Guatemalans want to have a say in local policies and want to improve public health for their community. Guatemalans are proud of their local customs and know how to implement technological change within cultural norms. Ultimately, the people in each community need to feel that they have agency to improve environmental health, which speaks to the utility of community-engaged research and interventions designed to arrive at the essential destination of clean air and clean water. As a research community concerned about Lake Atitlán, we need to help Atitlán residents to become citizen scientists and engage in productive efforts in their communities. The UVG already does this, but the scaling up of these efforts could make Lake Atitlán a global model for community-based environmental health solutions.

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