Systems Thinking for Effective Interventions in Global Environmental Health

Martha M. McAlister, Qiong Zhang, Jonathan Annis, Ryan W. Schweitzer, Sunny Guidotti, and James R. Mihelcic*

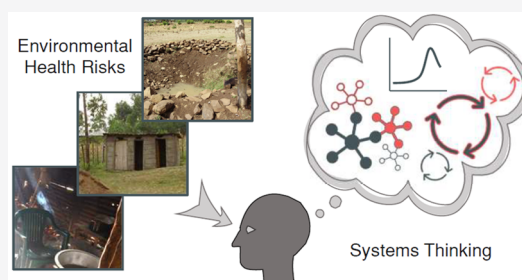Cite This: *Environ. Sci. Technol.* 2022, 56, 732−738

Read Online

ACCESS | Metrics & More | Article Recommendations

ABSTRACT: Environmental health risks such as household air pollution due to burning solid fuels, inadequate water, sanitation, and hygiene, and chemical pollution disproportionately affect the poorest and most marginalized populations. While billions of dollars and countless hours of research have been applied toward addressing these issues in both development and humanitarian contexts, many interventions fail to achieve or sustain desired outcomes over time. This pattern points to the perpetuation of linear thinking, despite the complex nature of environmental health within these contexts. There is a need and an opportunity to engage in critical reflection of the dominant paradigms in the global environmental health community, including how they affect decision-making and collective learning. These paradigms should be adapted as needed toward the integration of diverse perspectives and the uptake of systems thinking. Participatory modeling, complexity-aware monitoring, and virtual simulation modeling can help achieve this. Additionally, virtual simulation modeling is relatively inexpensive and can provide a low-stakes environment for testing interventions before implementation.

KEYWORDS: *sustainable development goals, WASH, household air pollution, chemical pollution, participatory modeling, complexity-aware monitoring, virtual simulation modeling*

INTRODUCTION

Globally, a significant proportion of the burden of disease (22% of total disability-adjusted life years) is attributable to environmental health risks, which the World Health Organization defines as "all the physical, chemical and biological factors external to a person, and all related behaviors, but excluding those natural environments that cannot reasonably be modified."[1] The health and well-being of the poorest and most marginalized populations are disproportionately affected by polluted environments.[2] Global health has been defined as, "an area for study, research, and practice that places a priority on improving health and achieving equity in health for all people worldwide."[3] We use the phrase *global environmental health* to refer specifically to the improvement of health for all people through the reduction of preventable environmental risks. This aligns with the definition given by the United States National Institute of Environmental Health Services.[4] Some notable areas of global environmental health are inadequate water, sanitation, and hygiene (WASH) services and practices, household air pollution due to the burning of solid fuels, and chemical pollution resulting from industrial malpractice (often in the informal sector[5,6]). These issues are relevant in development, humanitarian response, and environmental justice settings and across multiple scales, from individual behaviors to trans-national policies.

Systems thinking is described as an approach,[7] discipline,[8] conceptual framework,[9,10] perspective,[11] or simply a way of thinking[12] that is used to understand patterns of change in terms of underlying, self-organizing interrelationships. Here, the word "system" refers to any network of interacting parts that produces emergent behaviors, from massive systems like the global hydrologic cycle or the global economy to small systems like a latrine or a village council. It is important to note that while concepts such as "enabling environment" and "systems strengthening" incorporate elements of systems thinking (e.g., ref 13), they are not synonymous.

Governments and the global development community use periodic measurements of standard environmental health indicators to gauge national, regional, and global progress toward achieving human development goals (e.g., the WHO/UNICEF Joint Monitoring Program[14]). Systems thinkers recognize that these trends emerge from underlying structural properties. Like the bulk of an iceberg, which lies below the

water's surface, system structures are difficult to "see" using traditional monitoring methods.[15] They are described as the rules, incentives, function, or purpose of a system that produce its outputs and outcomes. For example, if exponential growth is observed in a variable, there must be a reinforcing feedback process driving that growth (e.g., a higher incidence of a communicable disease leads to higher exposure rates, which leads to a higher incidence, and so on). It also must be true that any balancing feedback processes in the system (e.g., deaths) are less significant than the reinforcing feedback. Systems thinkers use trends to formulate hypotheses about system structures by asking "why" and "how" questions. For example, why is the pattern occurring, and how are the relationships between components and across scales resulting in the observed trend?

In the past three to four decades of concerted investment in global environmental health, achieving and sustaining desired intervention outcomes has emerged as a recurrent challenge.[16,17] In this paper, we use systems thinking to hypothesize why this is such a persistent trend. Specifically, we focus on structural feedback processes, namely, learning. We suggest expanding the scope of global environmental health research and practice to include the consideration of influential paradigms (which are themselves influenced by historical, cultural, political, and environmental factors). Furthermore, we identify three practical methodologies for incorporating diverse perspectives, accelerating collective learning, and systematically reversing this trend. We start by defining the concept of complex systems and providing evidence that global environmental health systems are complex.

■ SYSTEMS AND COMPLEXITY

While Western academics began to coalesce their ideas around theoretical frameworks or principles like complex systems theory and complex adaptive systems in the 1970s,[18] holistic conceptual frameworks are recognized in many indigenous knowledge systems, such as those of the Kuna (Panama) and Quechua (Peru).[19] In general, systems thinking offers a means for better understanding complex problems. Systems thinking is often contrasted to reductionist thinking, which is an attempt to understand complex systems by intensely studying their constituent parts in relative isolation from each other. We do not argue that systems thinking should replace reductionist thinking in global environmental health, but rather for the increased uptake of systems thinking to complement the large body of knowledge compiled through reductionist research (see also refs 20 and 21).

Complex systems generally have the following characteristics: (1) they are comprised of a network of many components, (2) these components have nonlinear interactions like sudden transitions and tipping points, and (3) they display emergent structure and behavior which demonstrates relationships between scales. Networks are groups of interconnected or interrelated components (elements, factors, actors, things), and in complex systems those components do not act or change independently of each other, nor are they controlled centrally. As previously defined, global environmental health is an area of study, research, and practice concerned with inequity, particularly related to those human health outcomes which result from environmental risks. In the next few paragraphs, we will provide examples from the literature that help frame this field more holistically and

illustrate that global environmental health systems exhibit complexity characteristics.

First, networks exist at various scales within global environmental health systems and involve various categories of components. For an individual, environmental risk accumulates via exposure to a variety of hazards through multiple pathways for varying lengths of time.[1,22] Additionally, environmental hazards often result from, and are sustained or removed due to, anthropogenic activities (e.g., artisanal gold mining may involve processing lead-containing ore in or near homes,[5] and the global climate crisis[23]). This demonstrates that social and behavioral elements interact with physical and temporal elements to produce some emergent pattern of health risks and effects. At the community, district, or national level, it is widely thought that for environmental health services or interventions to be effective and sustainable, certain components or "building blocks" (e.g., institutional, monitoring, and financial systems) must be in place and functioning,[24] further demonstrating relationships across multiple domains.

Nonlinear behavior occurs when a change in one variable has a disproportionate impact on another variable; for example, dose–response curves often follow an S-shape. In global environmental health interventions, this might mean that certain parameters must be optimized before any significant change is observed in health outcomes. Mellor et al. found this to be the case when assessing water quality interventions; they observed tipping points in intervention efficacy that had to be reached to reduce early childhood diarrhea.[25] In market-based sanitation interventions, latent demand for improved toilets might be "triggered" by a promotional campaign or by the facilitation of connections with service providers, leading to increased uptake of improved toilets.[26] Also, while it seems intuitive that movement up the "energy ladder" (from biomass to cleaner cooking fuels like electricity) would have proportionate effects on health, this linear thinking has several shortcomings[27] and has not been validated by randomized control trials.[28,29]

Lastly, patterns of behavior occurring at one scale in global environmental health have implications on the structure and behavior of other scales. As previously mentioned, poor and marginalized individuals are more likely to experience a greater burden of disease than others. This leads to emergent behavior at the national level in which productivity losses due to environmental pollution have been estimated to be up to 1.33% in low-income countries, whereas in high-income countries this estimate is only 0.05%.[2] This could have far-reaching consequences, such as continual underinvestment by governments in measures to reduce environmental health risks (a reinforcing feedback loop). Conversely, reductions in environmental health risks, such as the wide-scale adoption of clean cookstoves, have the potential to benefit many aspects of sustainable development, like health, climate, gender equity, and livelihoods.[30]

In practice, a diverse set of tools have been developed in response to an increased awareness of the complexity of global environmental health. Qualitative frameworks like IRC's and Sanitation and Water for All's "building blocks" are meant to promote the development of holistic, context-specific interventions to guide WASH program planning. Members of Agenda for Change, the Sustainable WASH Systems Learning Partnership, and the Clean Cooking Alliance use "theories of change" in project and program development to formally outline causal hypotheses, which should in turn inform
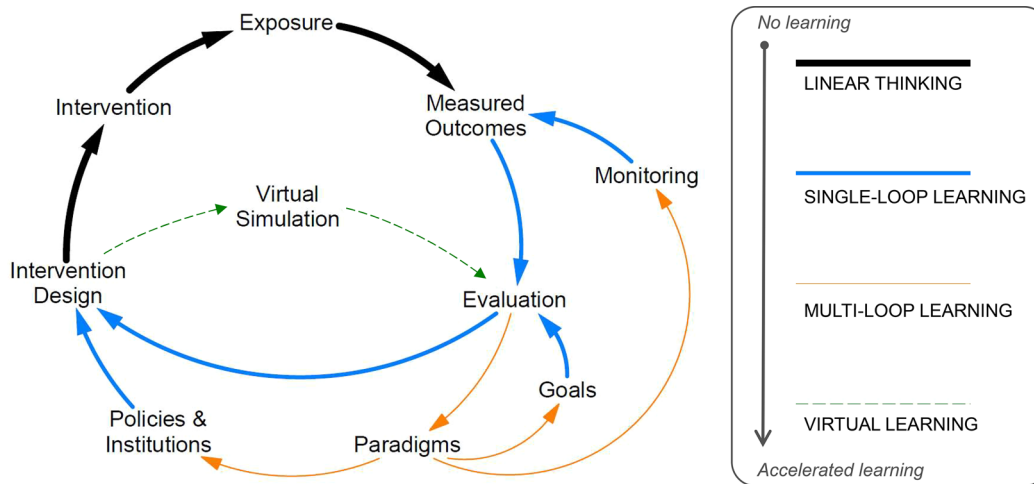
Figure 1. Evolution of learning in global environmental health research and practice. Arrows indicate influence.

appropriate sets of monitoring, evaluation, and learning objectives. Monitoring and assessment tools focused on the sustainability of program outcomes include UNICEF's Bottleneck Analysis Tool for WASH and the U.S. Agency for International Development (USAID)-Rotary International WASH Sustainability Index Tool. A shortcoming of some of these approaches is that they highlight the first aspect of complex systems (*they are comprised of a network of many components*) and may not be cognizant of nonlinearity and emergent behavior.

In the research community, Bayesian network analyses have been conducted to evaluate handpump sustainability in rural Ghana,[31] as well as water system functionality in Nigeria and Tanzania.[32] System dynamics, which includes tools like causal loop diagramming and stock-and-flow modeling, has been used to study the impact of biochar producing stoves on climate change,[33] the adoption of wastewater resource recovery systems in Belize,[34] and the sustainability of rural water services in Timor-Leste.[35] Implementation science, which is gaining traction in global environmental health applications, follows the tenets of systems thinking by emphasizing the "how" and "why" of intervention outcomes.[36,37] However, there is a need for increased documentation of systems approaches in WASH across diverse settings,[38] and in environmental health more broadly.[37] Additionally, few studies using systems methodologies in global environmental health reflect specifically on the design and implementation of interventions themselves (beyond social, environmental, and technical factors), though ref 39 is a notable exception.

■ HYPOTHESIS

We believe that many global environmental health interventions fail to produce or sustain desired outcomes because they are designed and implemented using linear thinking and single-loop learning, with a limited understanding of dynamic complexity. Linear thinking, a general tendency of most mental models,[40] does not account for the complex system characteristics described above. Mental models are representations of how a person or group believes a system will behave. They are shaped by perceptions, paradigms, and experiences and lead to expectations and decisions. In single-loop learning, advances are made toward reaching a goal, but without significant

change to existing mental models.[41] In other words, linear thinking is perpetuated within single-loop learning.

Figure 1 illustrates feedback structures which lead to learning. The heavy black arrows represent conventional linear thinking, which we posit has historically been the dominant mode of designing, implementing, and studying interventions. In this mindset, interventions are designed and then implemented, thereby hopefully leading to a change in environmental exposure and some measurable output or outcome. This process improves via a feedback loop (indicated by the blue arrows), in which measured outcomes are evaluated against desired outcomes (goals), and intervention designs are altered to reduce the discrepancy between them. In the 1990s, monitoring and evaluation gained traction as valuable pieces of this single-loop learning process,[42] and more recently, monitoring efforts have become increasingly focused on sustainability and equity.[43] While these changes are evidence of learning within the various communities of practice and research, the process is slow and too often based on trial-and-error, which can lead to unintended consequences.

We suggest that the global environmental health community needs to engage in more reflection and critique of pervasive paradigms and how they affect decision-making. Far from being just conceptualizations or theories, paradigms have practical implications on the design and implementation of environmental health interventions. For example, Workman found that neoliberal development ideologies (such as those leading to the decentralization of water governance) have a profound effect on water committee functionality in Lesotho.[44] Wells et al. discuss competing rationalities (e.g., "environmentality," conservationism) affecting decision-making in the case of a proposed wastewater system in Belize, and argue for a more inclusive and participatory approach toward situating the infrastructure in the local context.[45] Furthermore, paradigms may lead to biased data collection and analysis, such as underestimating uncertainty, believing that desired outcomes are more likely than undesired outcomes, and selection or confirmation bias.[41] Consider the possible effects of pervasive paradigms in the development sector. Development indicators are often collected at the household level (e.g., Demographic and Health Surveys and Multiple Indicator Cluster Surveys), ignoring intrahousehold disparities, assuming a universally accepted definition of household, and omitting significant

portions of the population like those on the move in fragile states (e.g., displaced people, migrants, pastoralists)[46] and people everywhere living in informal settlements.

We are primarily concerned with widely held or shared paradigms, those mindsets that are pervasive within the development, humanitarian, and governance sectors, because they are the most likely to have a systematic effect on intervention efficacy. By acknowledging the effects of paradigms, three additional feedback loops are created (thin orange arrows in Figure 1), increasing the potential for learning and adaptation. These feedback processes allow for the reframing of paradigms and for changes to underlying principles, known as double- and triple-loop learning, respectively.[47] For the purposes of this paper, we will refer to these processes as multiloop learning.

Finally, we incorporate virtual simulation in the diagram (using dashed green arrows) to illustrate how it accelerates learning by bypassing real-world interventions, which may take many years to implement and many more years to fully evaluate their sustainability. Importantly, virtual simulation is also much cheaper than an actual intervention and allows for experimentation that might be unethical in the real world.

■ OPPORTUNITIES

Here, we identify three practical approaches which can be used to facilitate accelerated learning in the context of global environmental health: (1) participatory modeling, (2) complexity-aware monitoring, and (3) virtual simulation modeling.

Participatory Modeling. As previously stated, mental models are representations of a person's assumptions and expectations regarding a system's behavior. Participatory modeling involves engaging a group of stakeholders in sharing their unique mental models and cocreating a formalized representation about a particular system or problem.[48] The underlying theory behind participatory modeling suggests that the *process* leads to collaborative learning and commitment to action.[49−51] Participatory modeling employs numerous methods and tools, including those which elicit stakeholder knowledge (e.g., interviews, surveys), those used to build models (e.g., cognitive mapping, social network analysis, agent-based modeling), and those which facilitate the process (e.g., role playing games, brainstorming).[48]

Participatory methodologies can help practitioners and researchers address power imbalances in the application of their work, given that the methods are accessible to all stakeholders[52,53] and that the facilitators employ mitigation techniques to prevent the perpetuation of systemic oppression.[54] Furthermore, participatory modeling can help participants (including facilitators) gain insight about complex systems.[55] For example, Valcourt et al. implemented a participatory factor mapping method in Ethiopia and Uganda that elicits stakeholders' ideas about the relative influence of various factors on the sustainability of WASH services.[56] They found that, by engaging in the process, stakeholders' understanding of WASH systems shifted to include more elements of complexity.[57]

Complexity-Aware Monitoring. Complexity-aware monitoring approaches are more likely to include data collection that is appropriate for complex systems, thereby leading to an increased awareness of the complexity in those systems (a reinforcing feedback loop). Some principles for complexity-aware monitoring include setting appropriate boundaries,

matching the pace of change in a system, and being flexible enough to capture unexpected changes and emergent behaviors.[58,59] Additionally, to improve accountability with stakeholders, monitoring data should be relevant to causal theories of change and reported in a timely manner.[60] In short, monitoring should not be performed just for the sake of tracking progress, but rather as a tool for gaining a more holistic understanding of the structural aspects of a given system. To this end, monitoring and evaluation approaches often benefit from the use of mixed quantitative and qualitative methods.

System mapping tools can be used at the start and iteratively throughout an intervention to select appropriate indicators for monitoring systemic change, to the extent possible given financial and human resources. For example, social, organizational, and other network analyses illuminate influential actors or critical components within an interconnected system (see refs 32 and 61 for examples of this in global environmental health). Those actors or components can then become the focus of intensive monitoring efforts. Similarly, causal loop diagrams, which map causal relationships, can reveal influential variables such as those that are included in multiple feedback loops. A particular advantage of these tools is their ability to synthesize both quantitative and qualitative data, which may be especially important when considering how and why different actors make decisions or relate to other actors.[62]

Complexity-aware monitoring also requires an awareness of the influence of time, including an understanding that effects can occur long after their causes due to buffers (accumulations of stocks) and delays. The depth of this awareness dictates the frequency of data collection and the time horizon over which an evaluation is conducted. Snapshots or singular data points do not contribute much to an understanding of systemic structure or complexity. Likewise, comparisons of before and after data points (think baseline and end-line surveys) hint only at linear trends, not the nonlinear behavior of complex systems. In general, dynamic awareness requires more frequent sampling, but this should be tailored to the specific goals of an intervention and targeted at components with high degrees of influence as described previously.

Virtual Simulation Models. Models are never perfect, being limited by the modelers' perspective, the quality and quantity of available data, and in the case of virtual models, software and hardware capabilities. However, within these limitations, modeling presents an alternative to costly, lengthy, and potentially harmful real-world experimentation.[41] In this paper, "virtual simulation model" refers to any type of digitized and quantified model that addresses complexity and can be simulated over time (e.g., stock-flow, agent-based). The primary purpose of virtual simulation in the context of global environmental health is to test model assumptions and potential strategies in a low-stakes environment and learn from the results to design better interventions.

With respect to virtual simulations, perhaps the greatest learning occurs when models reveal nonintuitive results. Dynamic models are built by defining relationships or rules between individual components or actors, not by imposing a predetermined outcome. As these relationships are simulated over time, unexpected behavior can emerge. In the real world, decision-makers are often surprised when an intervention not only fails but leads to worse conditions (a tendency of complex systems known as policy resistance). For instance, increased use of antibiotics leads to drug-resistant pathogens and poorly

targeted subsidization schemes sometimes lower users' willingness to pay for services in the future (see ref 41 for a longer list). Simulations of intervention strategies using dynamic models are also prey to unintended consequences, but unlike real systems, the rules and structure of a model are completely known to the modeler, making it easier to point to the cause of the resistance.

Flight simulators allow pilots to "experience" the consequences of their actions in a controlled setting. Similarly, management flight simulators are used to improve understanding of the complex dynamics of business and markets by allowing managers to see possible long-term outcomes of decisions.[63] In global environmental health, virtual simulation models can be used to test strategies or policies in a low-stakes environment. For example, Dianati et al. implemented a participatory model building exercise concerning household air pollution in informal settlements in which different policies were evaluated using a virtual stock-and-flow model.[64] They found that diverting available funds to air quality monitoring and health impact assessments would make the problem more visible and thus a higher priority for the local government, as well as other reinforcing effects. In another example using system dynamics modeling, Chalise et al. simulated intervention strategies for the sustained use of clean cooking systems in rural India.[39] They found that implementing consistent technical support for new technologies may be a key piece of the transition to cleaner cooking fuels. Mellor et al. used agent-based model simulations to understand the efficacy and compounding effects of WASH interventions in South Africa, finding that combinations of interventions may be necessary to significantly improve household water quality.[25] These examples illustrate the potential value of virtual simulation modeling as an in silico testing ground for environmental health intervention strategies.

■ CONCLUSION

Global environmental health systems are complex, displaying network attributes, nonlinear behavior, and relationships between scales. Therefore, to sustainably achieve desired environmental health outcomes, interventions must be designed, implemented, and monitored using systems thinking. We hypothesize that the consistent failure of global environmental health interventions can be traced to structural learning processes which have perpetuated linear thinking and pervasive humanitarian, development, and governance paradigms. Evolving these processes to promote systems thinking and critical reflection of influential paradigms can be achieved with three practical methodologies: (1) participatory modeling, (2) complexity-aware monitoring, and (3) virtual simulation modeling. The first two facilitate holistic and dynamic data collection, and participatory modeling can also help participants learn and practice systems thinking. Virtual simulation modeling leads to greater understanding of complexity by challenging what are often linear assumptions. Furthermore, virtual simulations can accelerate the pace of learning and help reduce unintended consequences when they are used to test intervention strategies before they are implemented.

■ AUTHOR INFORMATION

Corresponding Author

James R. Mihelcic — *Department of Civil & Environmental Engineering, University of South Florida, Tampa, Florida 33620, United States;* ◉ orcid.org/0000-0002-1736-9264; Email: jm41@usf.edu

Authors

Martha M. McAlister — *Department of Civil & Environmental Engineering, University of South Florida, Tampa, Florida 33620, United States;* ◉ orcid.org/0000-0002-5939-6340

Qiong Zhang — *Department of Civil & Environmental Engineering, University of South Florida, Tampa, Florida 33620, United States*

Jonathan Annis — *USAID Uganda Sanitation for Health Activity, Tetra Tech, Bugolobi, Kampala, Uganda*

Ryan W. Schweitzer — *Independent, Decatur, Georgia 30030, United States*

Sunny Guidotti — *Latin America and Caribbean Regional Office, UNICEF, Panama City 07144, Panama*

Complete contact information is available at:
https://pubs.acs.org/10.1021/acs.est.1c04110

Notes

Biography

Dr. James R. Mihelcic is the Samuel L. and Julia M. Flom Professor of Civil and Environmental Engineering. Dr. Mihelcic is internationally recognized for education and research contributions in the areas of sustainable water and nutrient management, and delivery of water, sanitation, and hygiene (WASH) in low- and middle-income countries. He is a Fellow with the Water Environment Federation (WEF) and Association of Environmental Engineering and Science Professors (AEESP), past president of the Association of Environmental Engineering and Science Professors (AEESP), a Board-Certified Environmental Engineering Member and past Board Trustee with the American Academy of Environmental Engineers & Scientists (AAEES). Dr. Mihelcic has also served two terms as a member of the U.S. Environmental Protection Agency's Chartered Science Advisory Board (SAB) and is currently an Associate Editor for *Environmental Science & Technology* and *Environmental Science & Technology Letters*. Dr. Mihelcic has authored over 200 published journal articles, book chapters, conference proceedings, and peer reviewed reports. He is also lead author for several engineering textbooks, including *Field Guide in Environmental Engineering for Development Workers: Water, Sanitation, Indoor Air* (ASCE Press, 2009); and *Environmental Engineering: Fundamentals, Sustainability, Design* (Third Edition, John Wiley & Sons, 2021).

■ REFERENCES

(1) Prüss-Ustün, A.; Wolf, J.; Corvalán, C.; Bos, R.; Neira, M. *Preventing Disease through Healthy Environments: A Global Assessment of the Burden of Disease from Environmental Risks*; World Health Organization: Geneva, 2016.

(2) Landrigan, P. J.; Fuller, R.; Acosta, N. J. R.; Adeyi, O.; Arnold, R.; Basu, N.; Nil; Baldé, A. B.; Bertollini, R.; Bose-O'Reilly, S.; Boufford, J. I.; Breysse, P. N.; Chiles, T.; Mahidol, C.; Coll-Seck, A. M.; Cropper, M. L.; Fobil, J.; Fuster, V.; Greenstone, M.; Haines, A.; Hanrahan, D.; Hunter, D.; Khare, M.; Krupnick, A.; Lanphear, B.; Lohani, B.; Martin, K.; Mathiasen, K. V.; McTeer, M. A.; Murray, C. J. L.; Ndahimananjara, J. D.; Perera, F.; Potočnik, J.; Preker, A. S.; Ramesh, J.; Rockström, J.; Salinas, C.; Samson, L. D.; Sandilya, K.; Sly, P. D.; Smith, K. R.; Steiner, A.; Stewart, R. B.; Suk, W. A.; van Schayck, O. C. P.; Yadama, G. N.; Yumkella, K.; Zhong, M. The Lancet Commission on Pollution and Health. *Lancet* **2018**, *391* (10119), 462−512.

(3) Koplan, J. P.; Bond, T. C.; Merson, M. H.; Reddy, K. S.; Rodriguez, M. H.; Sewankambo, N. K.; Wasserheit, J. N. Towards a Common Definition of Global Health. *Lancet* **2009**, *373* (9679), 1993−1995.

(4) NIEHS. Global Environmental Health; https://www.niehs.nih.gov/research/programs/geh/index.cfm (accessed 2021/2/16).

(5) Tirima, S.; Bartrem, C.; von Lindern, I.; von Braun, M.; Lind, D.; Anka, S. M.; Abdullahi, A. Environmental Remediation to Address Childhood Lead Poisoning Epidemic Due to Artisanal Gold Mining in Zamfara, Nigeria. *Environ. Health Perspect.* **2016**, *124* (9), 1471−1478.

(6) Buerck, A. M.; Usowicz, M.; Cunningham, J. A.; Khaliq, M. A.; Barrett, L. J. P.; Rakotoarisoa, L.; Rakotondrazaka, R.; Alfredo, K. A.; Sommariva, S.; Mihelcic, J. R. Health and Economic Consequences of Lead Exposure Associated with Products and Services Provided by the Informal Economy. *Environ. Sci. Technol.* **2021**, *55* (12), 8362−8370.

(7) Ramalingam, B.; Jones, H.; Reba, T.; Young, J. *Exploring the Science of Complexity: Ideas and Implications for Development and Humanitarian Efforts*; 285; Overseas Development Institute: London, 2008.

(8) Sweeney, L. B. Guidelines for Daily Systems Thinking Practice. *The Systems Thinker* **2001**, *12* (2), 6.

(9) Soderquist, C.; Overakker, S. Education for Sustainable Development: A Systems Thinking Approach. *Global Environ. Res.* **2010**, *14*, 193−202.

(10) Senge, P. *The Fifth Discipline*; Currency: New York, 2006.

(11) Morgan, P. The Idea and Practice of Systems Thinking and Their Relevance for Capacity Development. *Maastricht Eur. Cent. Dev. Policy.* **2005**, 1−33.

(12) Meadows, D. H. *Thinking in Systems: A Primer*; Wright, D., Ed.; Chelsea Green Publishing: White River Junction, VT, 2008.

(13) *Strengthening Enabling Environment for Water, Sanitation and Hygiene (WASH): Guidance Note*. UNICEF:2016.

(14) UNICEF; WHO. *Joint Monitoring Program*; https://washdata.org/data/household#!/dashboard/new.

(15) Karash, R. How to See "Structure". In *Systems Thinker*, 1997, *8*, 4, pp 6−7, https://thesystemsthinker.com/how-to-see-structure/.

(16) Landrigan, P. J.; Fuller, R.; Acosta, N. J. R.; Adeyi, O.; Arnold, R.; Basu, N.; Nil; Baldé, A. B.; Bertollini, R.; Bose-O'Reilly, S.; Boufford, J. I.; Breysse, P. N.; Chiles, T.; Mahidol, C.; Coll-Seck, A. M.; Cropper, M. L.; Fobil, J.; Fuster, V.; Greenstone, M.; Haines, A.; Hanrahan, D.; Hunter, D.; Khare, M.; Krupnick, A.; Lanphear, B.; Lohani, B.; Martin, K.; Mathiasen, K. V.; McTeer, M. A.; Murray, C. J. L.; Ndahimananjara, J. D.; Perera, F.; Potočnik, J.; Preker, A. S.; Ramesh, J.; Rockström, J.; Salinas, C.; Samson, L. D.; Sandilya, K.; Sly, P. D.; Smith, K. R.; Steiner, A.; Stewart, R. B.; Suk, W. A.; van Schayck, O. C. P.; Yadama, G. N.; Yumkella, K.; Zhong, M. The Lancet Commission on Pollution and Health. *Lancet* **2018**, *391* (10119), 462−512.

(17) *What Does It Take to Sustain Water, Sanitation, and Hygiene Outcomes? Lessons from Six Ex-Post Evaluations;* United States Agency for International Development: 2020.

(18) Castellani, B. *Map of the Complexity Sciences;* https://www.art-sciencefactory.com/complexity-map_feb09.html (accessed 2021/2/23).

(19) Apgar, J. M.; Argumedo, A.; Allen, W. Building Trans-disciplinarity for Managing Complexity: Lessons from Indigenous Practice. *Int. J. Interdiscip. Soc. Sci.* **2009**, *4* (5), 255−270.

(20) Zimmerman, J. B.; Westerhoff, P.; Field, J.; Lowry, G. Evolving Today to Best Serve Tomorrow. *Environ. Sci. Technol.* **2020**, *54* (10), 5923−5924.

(21) Fiksel, J. Designing Resilient, Sustainable Systems. *Environ. Sci. Technol.* **2003**, *37* (23), 5330−5339.

(22) Ezzati, M.; Kammen, D. M. Household Energy, Indoor Air Pollution, and Health in Developing Countries: Knowledge Base for Effective Interventions. *Annu. Rev. Energy Environ.* **2002**, *27* (1), 233−270.

(23) IPCC. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; Core Writing Team*; Pachauri, R. K., Meyer, L. A., Eds.; Geneva, 2015.

(24) Moriarty, P. *IRC Strategy Framework 2017−30: Building WASH Systems to Deliver the Sustainable Development Goals*; The Hague, 2017.

(25) Mellor, J. E.; Smith, J. A.; Learmonth, G. P.; Netshandama, V. O.; Dillingham, R. A. Modeling the Complexities of Water, Hygiene, and Health in Limpopo Province, South Africa. *Environ. Sci. Technol.* **2012**, *46* (24), 13512−13520.

(26) *Scaling Market Based Sanitation: Desk Review on Market-Based Rural Sanitation Development Programs; USAID Water, Sanitation, and Hygiene Partnerships and Learning for Sustainability (WASHPaLS) Project*; United States Agency for International Development: Washington, DC, 2018.

(27) Yadama, G. N. *Fires, Fuel & the Fate of 3 Billion: The State of the Energy Impoverished*; Oxford University Press, 2013.

(28) Smith, K. R.; McCracken, J. P.; Weber, M. W.; Hubbard, A.; Jenny, A.; Thompson, L. M.; Balmes, J.; Diaz, A.; Arana, B.; Bruce, N. Effect of Reduction in Household Air Pollution on Childhood Pneumonia in Guatemala (RESPIRE): A Randomised Controlled Trial. *Lancet* **2011**, *378* (9804), 1717−1726.

(29) Mortimer, K.; Ndamala, C. B.; Naunje, A. W.; Malava, J.; Katundu, C.; Weston, W.; Havens, D.; Pope, D.; Bruce, N. G.; Nyirenda, M.; Wang, D.; Crampin, A.; Grigg, J.; Balmes, J.; Gordon, S. B. A Cleaner Burning Biomass-Fuelled Cookstove Intervention to Prevent Pneumonia in Children under 5 Years Old in Rural Malawi (the Cooking and Pneumonia Study): A Cluster Randomised Controlled Trial. *Lancet* **2017**, *389* (10065), 167−175.

(30) Anenberg, S. C.; Balakrishnan, K.; Jetter, J.; Masera, O.; Mehta, S.; Moss, J.; Ramanathan, V. Cleaner Cooking Solutions to Achieve Health, Climate, and Economic Cobenefits. *Environ. Sci. Technol.* **2013**, *47* (9), 3944−3952.

(31) Fisher, M. B.; Shields, K. F.; Chan, T. U.; Christenson, E.; Cronk, R. D.; Leker, H.; Samani, D.; Apoya, P.; Lutz, A.; Bartram, J. Understanding Handpump Sustainability: Determinants of Rural Water Source Functionality in the Greater Afram Plains Region of Ghana. *Water Resour. Res.* **2015**, *51* (10), 8431−8449.

(32) Cronk, R.; Bartram, J. Factors Influencing Water System Functionality in Nigeria and Tanzania: A Regression and Bayesian Network Analysis. *Environ. Sci. Technol.* **2017**, *51* (19), 11336−11345.

(33) Whitman, T.; Nicholson, C. F.; Torres, D.; Lehmann, J. Climate Change Impact of Biochar Cook Stoves in Western Kenyan Farm Households: System Dynamics Model Analysis. *Environ. Sci. Technol.* **2011**, *45* (8), 3687−3694.

(34) Prouty, C.; Mohebbi, S.; Zhang, Q. Socio-Technical Strategies and Behavior Change to Increase the Adoption and Sustainability of

Wastewater Resource Recovery Systems. *Water Res.* **2018**, *137*, 107−119.

(35) Neely, K.; Walters, J. P. Using Causal Loop Diagramming to Explore the Drivers of the Sustained Functionality of Rural Water Services in Timor-Leste. *Sustain* **2016**, *8* (1), 1−18.

(36) Haque, S. S.; Freeman, M. C. The Applications of Implementation Science in Water, Sanitation, and Hygiene (WASH) Research and Practice. *Environ. Health Perspect.* **2021**, *129* (6), 1−10.

(37) Rosenthal, J.; Arku, R. E.; Baumgartner, J.; Brown, J.; Clasen, T.; Eisenberg, J. N. S.; Hovmand, P.; Jagger, P.; Luke, D. A.; Quinn, A.; Yadama, G. N. Systems Science Approaches for Global Environmental Health Research: Enhancing Intervention Design and Implementation for Household Air Pollution (HAP) and Water, Sanitation, and Hygiene (WASH) Programs. *Environ. Health Perspect.* **2020**, *128* (10), 1−12.

(38) Valcourt, N.; Javernick-will, a.; Walters, J.; Linden, K. System Approaches to Water, Sanitation, and Hygiene: A Systematic Literature Review. *Int. J. Environ. Res. Public Health* **2020**, *17* (3), 702.

(39) Chalise, N.; Kumar, P.; Priyadarshini, P.; Yadama, G. N. Dynamics of Sustained Use and Abandonment of Clean Cooking Systems: Lessons from Rural India. *Environ. Res. Lett.* **2018**, *13* (3). 035010.

(40) Sweeney, L. B.; Sterman, J. D. Thinking about Systems: Student and Teacher Conceptions of Natural and Social Systems. *Syst. Dyn. Rev.* **2007**, *23* (2−3), 285−311.

(41) Sterman, J. D. Learning from Evidence in a Complex World. *Am. J. Public Health* **2006**, *96* (3), 505−514.

(42) Valadez, J. J.; Bamberger, M. Evaluating Social Programs in Developing Countries. In *Monitoring and Evaluating Social Programs in Developing Countries: A Handbook for Policymakers, Managers, and Researchers*; World Bank Publications: Washington, DC, 1994; pp 1−34.

(43) van der Voorden, C.; Krukker, I. Behaviour, Sustainability, and Inclusion: Trends, Themes, and Lessons in Monitoring Sanitation and Hygiene. In *From Infrastructure to Services: Trends in monitoring sustainable water, sanitation, and hygiene services*; Schouten, T., Smits, S., Eds.; Practical Action Publishing: Rugby, UK, 2015; pp 109−135.

(44) Workman, C. L. Ebbs and Flows of Authority: Decentralization, Development and the Hydrosocial Cycle in Lesotho. *Water (Switzerland)* **2019**, *11* (2). 184.

(45) Wells, E. C.; Webb, W.; Prouty, C. M.; Zarger, R. K.; Trotz, M. A.; Whiteford, L. M.; Mihelcic, J. R. Wastewater Technopolitics on the Southern Coast of Belize. *Econ. Anthropol.* **2019**, *6* (2), 277−290.

(46) Tillett, W.; Trevor, J.; Schillinger, J.; Dearmey, D. Applying WASH Systems Approaches in Fragile Contexts: A Discussion Paper; 2020.

(47) Johannessen, Å.; Gerger Swartling, Å.; Wamsler, C.; Andersson, K.; Arran, J. T.; Hernández Vivas, D. I.; Stenström, T. A. Transforming Urban Water Governance through Social (Triple-Loop) Learning. *Environ. Policy Gov.* **2019**, *29* (2), 144−154.

(48) Voinov, A.; Jenni, K.; Gray, S.; Kolagani, N.; Glynn, P. D.; Bommel, P.; Prell, C.; Zellner, M.; Paolisso, M.; Jordan, R.; Sterling, E.; Schmitt Olabisi, L.; Giabbanelli, P. J.; Sun, Z.; Le Page, C.; Elsawah, S.; BenDor, T. K.; Hubacek, K.; Laursen, B. K.; Jetter, A.; Basco-Carrera, L.; Singer, A.; Young, L.; Brunacini, J.; Smajgl, A. Tools and Methods in Participatory Modeling: Selecting the Right Tool for the Job. *Environ. Model. Softw.* **2018**, *109* (August), 232−255.

(49) Vennix, J. A. M. *Group Model Building: Facilitating Team Learning Using System Dynamics*; John Wiley & Sons: Chichester, England, 1996.

(50) Hovmand, P. S. *Community Based System Dynamics: Lessons from The Field;* Springer: 2014.

(51) Duboz, R.; Echaubard, P.; Promburom, P.; Kilvington, M.; Ross, H.; Allen, W.; Ward, J.; Deffuant, G.; Garine-Wichatitsky, M. de; Binot, A. Systems Thinking in Practice: Participatory Modeling as a Foundation for Integrated Approaches to Health. *Front. Vet. Sci.* **2018**, *5* (NOV), 1−8.

(52) Ballard, E.; Werner, K.; Priyadashini, P. Boundary Objects in Translation: The Role of Language in Participatory System Dynamics Modeling. *Syst. Dyn. Rev.* **2021**, *37*, 1−23.

(53) Jordan, R.; Gray, S.; Zellner, M.; Glynn, P. D.; Voinov, A.; Hedelin, B.; Sterling, E. J.; Leong, K.; Olabisi, L. S.; Hubacek, K.; Bommel, P.; BenDor, T. K.; Jetter, A. J.; Laursen, B.; Singer, A.; Giabbanelli, P. J.; Kolagani, N.; Carrera, L. B.; Jenni, K.; Prell, C. Twelve Questions for the Participatory Modeling Community. *Earth's Future* **2018**, *6* (8), 1046−1057.

(54) Butler, C.; Adamowski, J. Empowering Marginalized Communities in Water Resources Management: Addressing Inequitable Practices in Participatory Model Building. *J. Environ. Manage.* **2015**, *153*, 153−162.

(55) Scott, R. J.; Cavana, R. Y.; Cameron, D. Recent Evidence on the Effectiveness of Group Model Building. *Eur. J. Oper. Res.* **2016**, *249* (3), 908−918.

(56) Valcourt, N.; Walters, J.; Javernick-Will, A.; Hollander, D. *Summary Report of Baseline Iterative Factor Mapping and Learning Analyses in Ethiopia and Uganda*; Washington, DC, 2019.

(57) Valcourt, N.; Walters, J. *Assessment of Shifts in Stakeholder Understanding of WASH Systems*, 2021.

(58) Hollander, D.; Ajroud, B.; Thomas, E.; Peabody, S.; Jordan, E.; Javernick-Will, A.; Linden, K. Monitoring Methods for Systems-Strengthening Activities toward Sustainable Water and Sanitation Services in Low-Income Settings. *Sustain.* **2020**, *12* (17). 7044.

(59) *Program Cycle Discussion Note: Complexity-Aware Monitoring*; United States Agency for International Development: 2018.

(60) Thomas, E.; Brown, J. Using Feedback to Improve Accountability in Global Environmental Health and Engineering. *Environ. Sci. Technol.* **2021**, *55* (1), 90−99.

(61) Narayan, A. S.; Fischer, M.; Lüthi, C. Social Network Analysis for Water, Sanitation, and Hygiene (WASH): Application in Governance of Decentralized Wastewater Treatment in India Using a Novel Validation Methodology. *Front. Environ. Sci.* **2020**, *7* (January). DOI: 10.3389/fenvs.2019.00198.

(62) Global Obesity Prevention Center at Johns Hopkins; Global Knowledge Initiative; LINC; ResilientAfrica Network.*SPACES MERL: Systems and Complexity White Paper*; United States Agency for International Development: 2016.

(63) Kim, D. H. Management Flight Simulators: Flight Training for Managers (Part I). *Syst. Thinker* **1992**, *3* (9), 5−6.

(64) Dianati, K.; Zimmermann, N.; Milner, J.; Muindi, K.; Ezeh, A.; Chege, M.; Mberu, B.; Kyobutungi, C.; Fletcher, H.; Wilkinson, P.; Davies, M. Household Air Pollution in Nairobi's Slums: A Long-Term Policy Evaluation Using Participatory System Dynamics. *Sci. Total Environ.* **2019**, *660*, 1108−1134.