

Rural Sanitation Sustainability Dynamics: Gaining Insight through Participatory and Simulation Modeling

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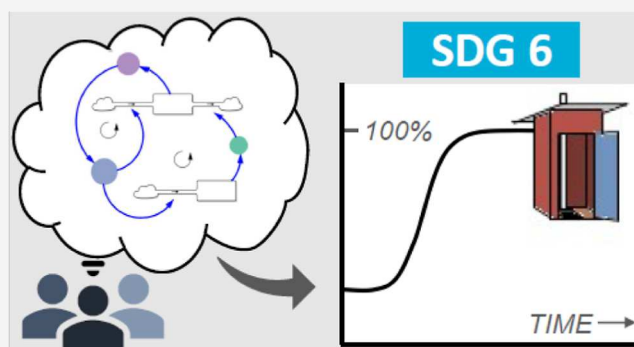
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Supporting Information

ABSTRACT: Improved sanitation provides many benefits to human health and well-being and is integral to achieving Sustainable Development Goal Six. However, many nations, including most of sub-Saharan Africa, are not on track to meeting sanitation targets. Recognizing the inherent complexity of environmental health, we used systems thinking to study sanitation sustainability in Uganda. Our study participants, 37 sanitation actors in three rural districts, were engaged in interviews, group model building workshops, and a survey. The resulting model was parametrized and calibrated using publicly available data and data collected through the Uganda Sanitation for Health Activity. Our simulations revealed slippage from improved sanitation in all study districts, a behavior reflected in real interventions. This implies that systemic changes—changes to the rules and relationships in the system—may be required to improve sanitation outcomes in this context. Adding reinforcing feedback targeting households' perceived value of sanitation yielded promising simulation results. We conclude with the following general recommendations for those designing sanitation policies or interventions: (1) conceptualize sanitation systems in terms of reinforcing and balancing feedback, (2) consider using participatory and simulation modeling to build confidence in these conceptual models, and (3) design many experiments (e.g., simulation scenarios) to test and improve understanding.

KEYWORDS: group model building, latrine, mixed methods, SDGs, sub-Saharan Africa, system dynamics, systems thinking, WASH



INTRODUCTION

Sustained household and community adoption of improved sanitary behaviors and practices promotes human health and wellness (e.g., by reducing enteric infections¹ and gender-based violence²) and offers many other societal and environmental benefits.³ Improved sanitation facilities include “flush/pour flush toilets connected to piped sewer systems, septic tanks, or pit latrines; pit latrines with slabs (including ventilated pit latrines); and composting toilets.”⁴ Globally, sanitation access has steadily increased in recent decades, driven by public funding coupled with technological and institutional innovations and adaptations. However, inequity persists at multiple scales (e.g., across and within regions, nations, and communities). For instance, some populations in high income countries remain unserved or poorly served,⁵ as do people living in fragile contexts such as conflict zones.⁶ Most nations in sub-Saharan Africa are backsliding or progressing too slowly to meet sanitation targets inspired by Sustainable Development Goal (SDG) Six (“ensure availability and sustainable management of water and sanitation for all”).⁴

Interventions aimed at improving sanitation outcomes for rural households in sub-Saharan Africa have had some success in the short term, but long-term monitoring and program evaluations often reveal reversion to unimproved sanitation or open defecation.^{7–9} Many factors have been identified as enablers or barriers to uptake and sustainability of improved sanitation in this context (e.g., markets, education, peer influence).^{10,11} These contextual factors are highly interrelated to each other, forming networks of factors from which specific sanitation outcomes emerge. For example, distinct outcomes such as latrine ownership and latrine usage might result from different factor networks that likely overlap and depend on one another.¹² Furthermore, the roles and responsibilities of

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sanitation governance are distributed among numerous actors, who are often challenged by a lack of coordination between and among different institutions.^{13,14} All these attributes are characteristic of complex systems and therefore underscore the applicability of *systems thinking* to accelerate actionable learning about rural sanitation uptake and sustainability.¹⁵

In systems thinking, interacting components are considered holistically to explore the underlying drivers of a particular pattern such as a persistent challenge. The network of interacting components being studied (i.e., the “system”) may be subjected to exogenous constraints or shocks over time, but the system’s ability to adapt to externalities is based on its internal structure. The goal of systems thinking is to understand the internal structure which drives a specific behavior.¹⁶ This can be achieved, in part, by creating virtual simulation models which test and strengthen the modelers’ understanding. The rules and relationships (i.e., structure) of these quantitative, *system dynamics* models are formulated according to the modeler’s dynamic hypothesis—a conceptual understanding about the feedback processes driving the studied behavior.¹⁷ Therefore, model parameters (i.e., inputs) are considered secondarily to the model structure. If the behavior does not emerge endogenously from the model structure, it is not considered to be a useful model.¹⁸

System dynamics modeling has been applied to a variety of complex health challenges, including cocaine addiction,¹⁹ polio eradication,²⁰ community health,²¹ and food security,²² often leading to policy insights and action. Applications of systems thinking in water, sanitation, and hygiene (WASH) research and practice are reportedly on the rise, but many documented cases lack an explicit analysis of component interactions, focus on water supply more often than sanitation or hygiene, and are inaccessible to local WASH decision makers.²³ One practical methodology that provides an accessible format for addressing complex component interactions is *group model building*.

Group model building is a participatory approach stemming from system dynamics.^{24,25} Well-facilitated group model building can lead to increased stakeholder alignment, understanding of complexity, and commitment to action.^{26,27} Indeed, group model building workshops convened in Uganda and Ethiopia on water service delivery helped to align participants’ understanding of complex issues.²⁸ The approach has also been successfully demonstrated in other development applications, such as household energy,²⁹ small-scale agriculture,³⁰ and rural livelihoods within the food-energy-water nexus.³¹ However, there has been limited application, if any, of these methods to rural sanitation.

Sanitation for all is one of many socio-environmental challenges that have benefited from centuries of reductionist insight, but now require more holistic approaches such as systems thinking to achieve sustainable impacts.³² In part, we present our research as an example, to be adapted and improved, for readers who are also seeking to apply systems thinking to environmental health and science. In our study, we used mixed methods, including group model building, to answer the following two questions: (1) how can the historic uptake and sustainability of sanitation services in rural Uganda be explained through system dynamics? and (2) How can system structures be altered or strengthened to promote sustainable sanitation outcomes that outlast intervention time frames? Our informants and participants were sanitation actors in three districts in Uganda. Together, we produced a simulation model that represents structural dynamics of rural

sanitation in this context, according to the participants’ understanding. We believe that the model itself is a valuable description of a complex socio-environmental system which can encourage new ways of thinking about and envisioning sanitation for all. Our findings suggest that in rural Uganda, households’ perceived value of sanitation may be highly influential in driving sanitation outcomes (research question 1). After formulating and testing several “what-if?” scenarios, we found that structural (i.e., systemic) changes may be needed to shift sustained sanitation outcomes toward SDG sanitation targets. We hypothesize that introducing a feedback mechanism, such as social reinforcement through public commitments and leadership development, would increase households’ perceived value of sanitation and lead to long-term sustainability without the need for continuous external support (research question 2).

METHODS

Study Context and Overview. Subnational governance plays a key role in enabling access to improved sanitation, by enhancing or limiting the effectiveness of national sanitation policies.³³ Huston et al. found that district-level bodies were an effective platform for learning and knowledge dissemination and that actors at this level were representative of key roles and perspectives related to water governance.³⁴ We have assumed that this also applies to sanitation governance in Uganda, and therefore selected three rural districts, hereafter referred to as the central east, central west, and northern study districts. Participants included representatives from the district government departments of Water, Health (specifically, Environmental Health), Education, Community Development, and Administration. Local Councils (elected) and Civil Society Organizations were represented in two of the study districts.

With assistance from the United States Agency for International Development Uganda Sanitation for Health Activity (USHA), we engaged the participants in individual interviews, group model building workshops, and a written survey. These activities occurred over a 10 week period from January to March 2022. See Figure 1 for an outline of our

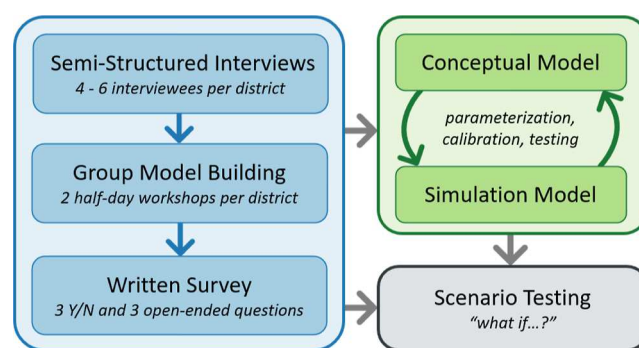


Figure 1. Outline of the study methods and procedure.

procedure. The study was conducted in accordance with Uganda’s guidelines on social and behavioral research. Review of the activities by the Uganda National Council of Science and Technology was not required as these activities posed no additional risk to participants beyond normal activities. The study protocol (STUDY003667) was deemed “exempt” by the Institutional Review Board of the University of South Florida. In-depth details on the study context and methods (including

the interview guide, workshop agendas, and survey questionnaire) can be found in the [Supporting Information](#).

Semi-Structured Interviews. Before engaging the study participants in a workshop setting, the first author conducted interviews with the participants individually to gather baseline information about their perspectives on the local WASH situation (the focus of the study was later refined to sanitation, as it was frequently stated as receiving less attention than water). The semistructured interviews³⁵ lasted between 20 and 60 min and were conducted in person at the interviewees' offices. After receiving information about the study purpose and structure, each interviewee gave their consent verbally to participate in the study.

In total, 14 interviews were completed. The interview data (notes and/or transcripts) were analyzed using a method adapted from *purposive text analysis*,³⁶ which is rooted in *grounded theory*.³⁷ In our procedure, we generated causal maps (word-and-arrow diagrams) from lists of causal relationships and their polarities, which were derived from deductive coding of the interview data (Appendix B of the [Supporting Information](#)).

Group Model Building. Our group model building process included two half-day workshops per study district, facilitated by the first author and USHA staff. The time between workshops ranged from one day to one month. We aimed to include up to ten participants at each workshop, a typical group size for group model building sessions that allows for diversity in perspectives without excluding anyone from discussions.²⁴

The purpose of Workshop One was to explore in-depth the causal relationships deduced from the interview data, to introduce the participants to the concepts of feedback and structure in the context of system dynamics, and to elicit a causal map representing a shared mental model. We guided discussions to gain a common understanding of system behavior (with respect to sanitation coverage over time), factor definitions, factor relationships, and their relative importance. For both Workshop One and Two, we adapted group model building scripts³⁸ to our purposes.

Next, we constructed a stock-flow simulation model to represent the salient structural dynamics identified during the interviews and Workshop One. These quantitative models were built using Vensim DSS software and following best practices in system dynamics modeling, as outlined in ref 39. To help delineate system boundaries, we included in the model the sanitation challenges ranked as the most important by the participants. District-specific model parameters were extracted from publicly available data (e.g., from the Uganda Bureau of Statistics) as well as assessment and monitoring data collected in the USHA target districts. Parameters for which no data were readily available were calibrated so that the model output matched the general trend of the reference mode (sanitation coverage over time) for each district. These unknown parameters were recalibrated later in a more rigorous process (described below).

The purpose of Workshop Two was to build more confidence in the model structure. Involving participants in the validation process likely leads to a better simulation model and may also lead to changes in their mental models.⁴⁰ We introduced each major assumption used to build the simulation model and discussed its validity until a consensus was reached. This ensured that the model elements and relationships (stocks, rates, variables, parameters, and delays) conformed to

the information provided by the participants. Furthermore, we reiterated that we were not attempting to represent every aspect of rural sanitation; too many feedback loops tend to muddle rather than clarify and improve understanding. The participants helped to prioritize what they believed were the most significant drivers of sanitation outcomes.

After making the changes suggested in Workshop Two discussions, and further iterative adjustments based on behavior reproduction and extreme conditions tests,⁴¹ the model was distilled to a qualitative causal loop diagram representing its endogenous structure and dynamics. This causal loop diagram (dynamic hypothesis) was presented to USHA staff in a two hour virtual workshop for further validation, with the intent of elaborating on the model structure and balancing any potential biases related to the participants' respective positions. The USHA staff agreed with the dynamic hypothesis and were able to provide some additional nuance, such as the need for trained sanitation service providers (e.g., masons and pit diggers). We also discussed how market-based intervention strategies could be included in scenario testing.

Survey. At the conclusion of the second workshop, the participants were asked to fill in a brief written survey containing three yes or no questions and three open-ended questions. The questionnaire was designed to collect data on whether the participants experienced any changes in perspective regarding the sanitation situation in their district. However, very few participants were involved in all phases of group model building, from the preliminary interviews to the final workshop. Instead, invited participants would often send a representative in their place to participate in the workshop sessions. This challenge of attracting and maintaining attendees should be taken into consideration when planning workshop timing and incentives. The number of people engaged in each stage of the participatory process is shown in [Table 1](#).

Table 1. Number of Interviewees and Workshop Attendees for Each Study District^a

study district	interviews	workshop one	workshop two	survey	total participants
central east	4	11	8	6	14
central west	6	8	7	6	13
northern	4	7	6	6	10
all	14	26	21	18	37

^aNote the total number of participants for each district does not equal the sum of that row because some people participated at more than one stage.

Model Calibration and Evaluation. We finalized the model via a quantitative calibration and evaluation process. To begin, we assigned Uganda national averages for known parameters (credit access, household size, households in the lowest wealth quintile, leaders as role models, local government as role model, median educational attainment, and population growth rate). We then calibrated the unknown parameters by fitting the simulation results to national data from the WHO/UNICEF Joint Monitoring Program (JMP) from the year 2000 to 2020.⁴² Specifically, we selected rural household data, disaggregated by the sanitation service level (Open Defecation, Unimproved, Limited, and Basic). No such long-term disaggregated data were available at the district level.

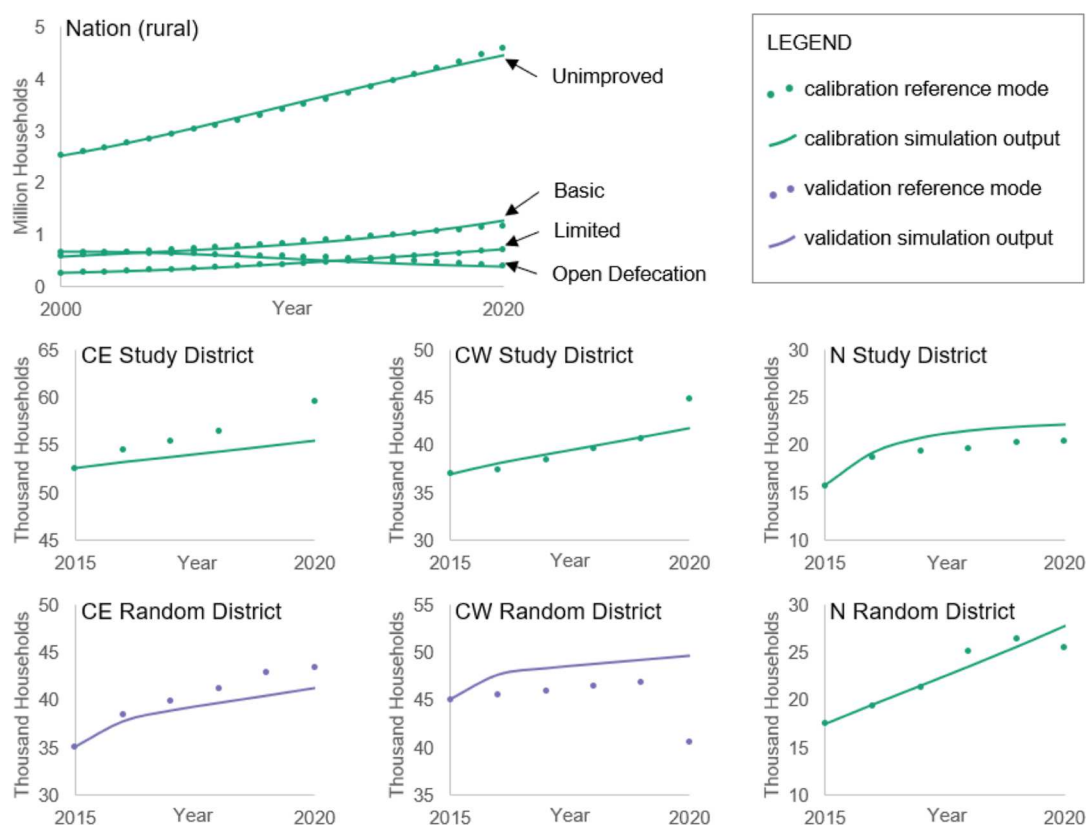


Figure 2. Calibration/validation simulation outputs for sanitation coverage are shown with reference modes (CE = central east, CW = central west, N = northern). For the districts, sanitation coverage was assumed to include all sanitation service levels except for open defecation. Statistics and reference mode data sources are given in Table S5.

The calibrated parameter values were found using the optimization function in Vensim DSS.

Next, we conducted a sensitivity analysis to determine which of the unknown exogenous parameters (i.e., model inputs) had a significant effect on the simulation outcomes. This helped us to determine which of the unknown parameters could be held constant across the districts and which still needed to be calibrated or estimated for each study district. We recalibrated the district-specific parameters for each of the study districts and one randomly selected district, using data from annual Ministry of Water and Environment (MWE) Performance Sector Reports (2015–2020).⁴³ These reports listed a sanitation coverage percentage, which we assumed to include all service levels except Open Defecation.

Finally, using the correlation and regression data analysis functions in Microsoft Excel, we developed equations relating the calibrated district-specific parameters to other parameters so that their values could be estimated for any district. For example, we found that the ideal enforcement frequency could be estimated from the initial open defecation percentage, according to a linear equation. We then parametrized and simulated the model for two randomly selected districts (each from a different USHA cluster) and compared these simulation results to data from the MWE Performance Sector Reports.

RESULTS AND DISCUSSION

Model Calibration and Evaluation. For the randomly selected districts, comparing the simulation results to actual data returned root mean squared percent error of no more than ten percent. This indicates that the model structure and

parameters adequately reproduce observed sanitation trends.⁴⁴ The calibration and validation simulation results are represented graphically along with their reference modes in Figure 2.

Survey. Eighteen participants responded to the written questionnaire. Results for the yes or no questions are provided in the Supporting Information. Responses to the open-ended questions were analyzed via deductive coding, where each respondent could have multiple thematic codes assigned to their responses. When asked, what are the most pressing challenges to achieve sustainable WASH services in your district?, most respondents ($n = 16$) mentioned the theme “funding.” More than half of respondents ($n = 11$) referred to the challenge of overcoming unfavorable or ambivalent mindsets toward WASH (mostly sanitation), which we coded as “sensitization.” A complete list of codes and exemplary responses to this question are included in Appendix F of the Supporting Information. Table 2 shows the list of codes deduced from responses to the question, what ideas do you have for improving WASH services in your district? Many of the ideas for improvement were directly related to the challenges identified by the respondents, indicating several potential leverage points for improving sanitation outcomes in rural Uganda.

Scenarios. Simulation models can help to test assumptions and reveal insights about dynamic behavior that cannot be realized with a static model.⁴⁵ Theoretically, this is due to humans’ bounded rationality when attempting to understand the dynamics of complex systems.⁴⁶ System dynamics models specifically are more suited for exploratory learning and high-

Table 2. Survey Respondents’ Ideas for Improving Their District’s WASH Situation^a

code	n	example
sensitization	11	“continue to sensitize the community on the value of WASH”
funding	7	“advocate for improved funding while ensuring that the available funds are put to the right use”
policy	6	“need to bring on board a holistic approach where all sectors are involved in WASH services in the district”
role models	5	“once in a while visiting homesteads with the leaders/ political wing”
enforcement	4	“regular inspections by the health department”
monitoring	3	“routine monitoring and follow up of community participation in WASH activities”
planning	3	“plan and budget for software activities on WASH”
community capacity	2	“engage the community to enhance their capacities”
household finance	2	“support communities with income generating initiatives to enable them earn enough to invest in sanitation improvement”
school	2	“implement school WASH activities to enhance behavior change”
staff capacity	2	“build capacity of the existing WASH staff through trainings”
water access	2	“improve safe water coverage”
partnership	1	“involve more implementing partners in WASH related activities”
peers	1	“embrace having model villages or parishes per year per sub-county”

^aThe number of respondents mentioning each thematic code and exemplary responses are provided.

level policy design than for planning the details of policy implementation.¹⁸ In developing scenarios for testing, we were interested foremost in understanding the dynamic effects of altering certain parameters or structures in the model rather than forecasting intervention outcomes. Therefore, in addition to the status quo (business as usual) scenario, we designed seven simulation scenarios, wherein only one component of the model was modified at a time. These can be interpreted as “what if?” scenarios aimed at learning about the consequences of a particular intervention strategy. For example, “What if everyone could afford to build an improved latrine, starting now?” (household finance scenario).

Figure 3 shows the model conceptually, as a causal loop diagram, and highlights the components modified in the scenarios. Five of the scenarios were designed according to the leverage points identified in the survey analysis. Specifically, we chose to modify components that were mentioned by more than one participant ($n > 1$) and were present in the model (namely, “sensitization,” “role models,” “enforcement,” “household finance,” and “school”). The supply scenario was suggested by USHA staff and designed to explore the effects of the supply components of a market-based approach. In the seventh scenario, no external funding, we switched off external funding and resources to understand how the “leave no one behind” balancing loop contributes to sanitation trends. In these scenarios, it is important to note that when we modified a component within a feedback loop, the component became exogenous and was no longer affected by other components of the model. For example, for the duration of the continuous sensitization scenario, sanitation sensitizations were not affected by district sanitation funding and resources. The scenarios are described in more detail below.

Status Quo. In this scenario, the “diminishing returns” balancing loops tend to limit the reinforcing action of the “success to the successful” loop, resulting in a relatively stable equilibrium. Ideally, the “leave no one behind” balancing loop would help the system seek an equilibrium close to universal improved sanitation, but external resources are spread thin geographically and among competing development priorities. Furthermore, because external resources generally decline when sanitation improves, district governments lose the ability to maintain higher levels of improved sanitation among their constituent households. For our purposes, “equilibrium” refers to the state at which the effects of different feedback loops are balanced out. This is usually characterized by behavior that is stagnant or is in controlled oscillations.

Continuous Sensitization. In this scenario, the frequency of sanitation sensitization becomes ideal. In other words, sensitizations occur frequently enough to improve and maintain households’ perceived value of sanitation over time. It is assumed that, without periodic reminders, households’ perceived value of sanitation (and therefore, adherence to improved sanitary behaviors) decreases over time. This could be driven in part by migration and other population changes but also by a perceived lack of urgency or immediacy with respect to improving or maintaining sanitation infrastructure and behaviors. In the status quo, the frequency of sensitizations is dependent on the sufficiency of funding for the district extension agents as sanitation sensitizations are seen as a core function of district governments.

Household Finance. In this scenario, all households become able and willing to access financial capital (e.g., through microloans for individuals or groups) to overcome affordability and/or liquidity barriers. Therefore, this scenario removes any financial barriers that prevent households from constructing an improved latrine. In the status quo, households in the lowest wealth quintile that want to construct an improved latrine model but cannot access the necessary capital build an unimproved latrine instead. Unimproved latrines are assumed to be within financial reach of all households.

Law Enforcement. In this scenario, the frequency of sanitation law enforcement (e.g., Public Health Act) becomes ideal. Therefore, households that have no desire for a latrine are forced to build either an improved or an unimproved latrine, depending on their financial situation. The latrine construction rate, however, is still limited by the availability of sanitation service providers (e.g., pit diggers and masons). In the status quo, the enforcement frequency is dependent on the sufficiency of funding for district health inspectors.

No External Funding. In this scenario, district government funding is dependent only on national funding, which is an exogenous parameter. In the status quo, the sufficiency of funding is poor and has a general downward slope (national funding allocations are assumed to decrease over time as the number of districts rise), but also is responsive (after a reporting delay) to the district’s open defecation status. “Sufficiency of funding” is defined in the model as “total funding,” the sum of national funding and external (bi- or multilateral) resources, divided by “funding needed.” Funding needed is a calibrated (i.e., theoretical) parameter because the actual amount of money needed to sufficiently fund the district government’s sanitation-related functions is unknown.

Role Model. In this scenario, the effectiveness of sanitation sensitizations increases by having full participation of local (e.g., subcounty or parish level) government officials and

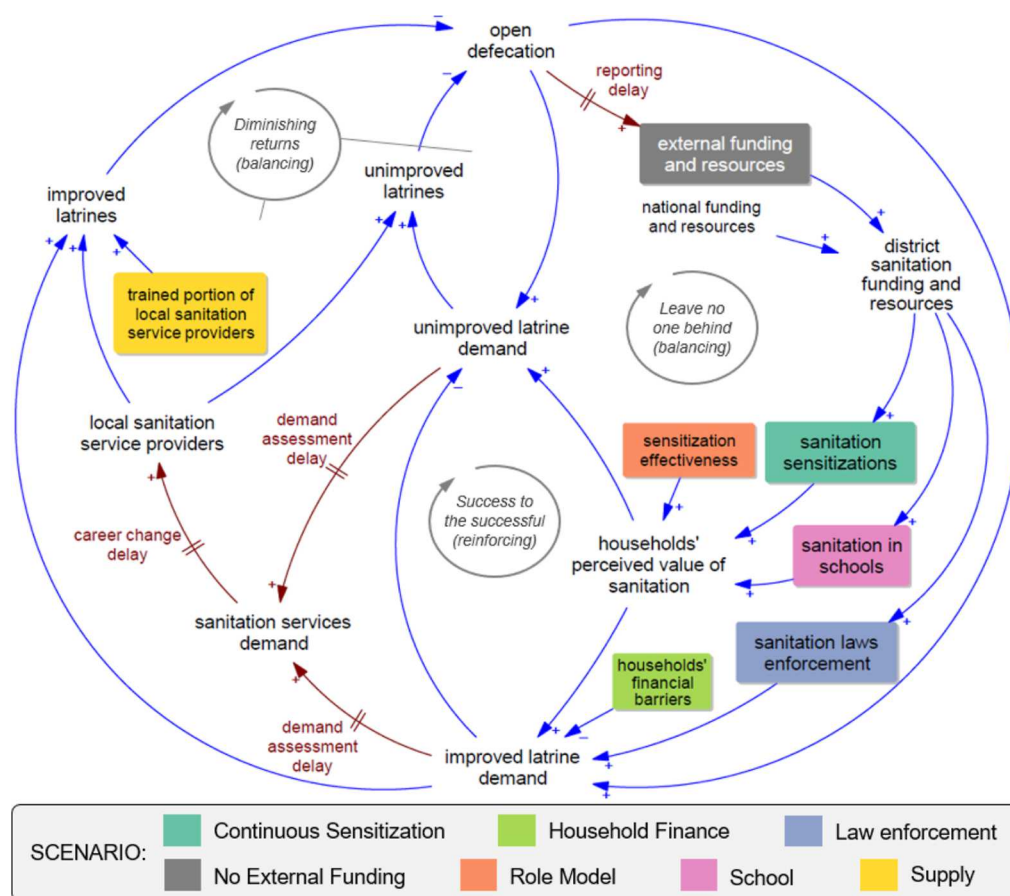


Figure 3. Causal loop diagram showing the endogenous structure of the model and the components of the model (in color-coded boxes) that were modified in each of the seven scenarios. Arrows indicate causal relationships, where a change in the variable at the tail of an arrow causes a change in the variable at the arrow's head in the same (+) or opposite (−) direction, all else being equal. Slash marks (//) across arrows indicate delays.

village leadership at sensitization or mobilization events. The intervention is limited to the extent that sensitization effectiveness is dependent on peer pressure, as opposed to role model participation. In the status quo, the role model factor is a constant value based on the observed participation of local leaders at USHA sanitation mobilization sessions.

School. In this scenario, sanitation access in schools becomes 100%, meaning that the Government of Uganda's target pupil to stance ratio is achieved for both sexes at all schools. This improves the effect that schools have on maintaining households' perceived value of sanitation, but this effect is still limited by median educational attainment (retention years in school). The sanitation in schools effect follows from the assumption that the more years an individual spends in a school with improved sanitation, the less that individual needs continuous sensitization regarding the value of sanitation (this agrees with findings from ref 10). In the status quo, sanitation access in schools is dependent on district resources (but never dips below 30%).

Supply. This scenario is based on the supply component of a market-based sanitation services approach. USHA's market-based sanitation implementation approach, as well as other market-based strategies (e.g., adopted by the Uganda Ministry of Health in March 2022), include financing, engagement, and institutional strengthening objectives in addition to supply and demand activation. In our scenario, all local laborers (pit diggers and masons) become trained to construct improved latrines, which removes the supply side barrier of too few

trained laborers. In the status quo, around five percent of laborers are trained, which limits the rate of improved latrine construction.

We tested the scenarios separately to understand the effects of each on the dynamic behavior of the system. The initial time for the simulations was 2015, the intervention start time was 2023, the final time was 2065, and the time step was one-quarter year. System dynamics models are generally not well-suited for forecasting behavior.¹⁸ Instead, they are built to explain and better understand historic patterns of behavior from a systems thinking perspective. We chose a time frame of 50 years because we expect that contextual parameters would likely change by the end of that time, whereas in the model, the exogenous parameters remain constant. On the other hand, too short of a time frame would provide little insight about how feedback loop dominance might shift under different scenarios.

Insights. To be clear, our study participants were only a portion of those involved with and affected by rural sanitation in Uganda, meaning that our results are affected by sampling bias. Readers must also consider potential omissions and biases in our model and simulation scenarios originating from the participants' respective worldviews. Furthermore, our study was process-oriented and focused on the high-level systemic and dynamic implications of certain paradigms, policies, or intervention strategies. For this reason, we purposefully refrained from presenting quantitative predictions based on our simulations (e.g., scenario A leads to X % improved sanitation for district B by year Y). Instead, here we discuss

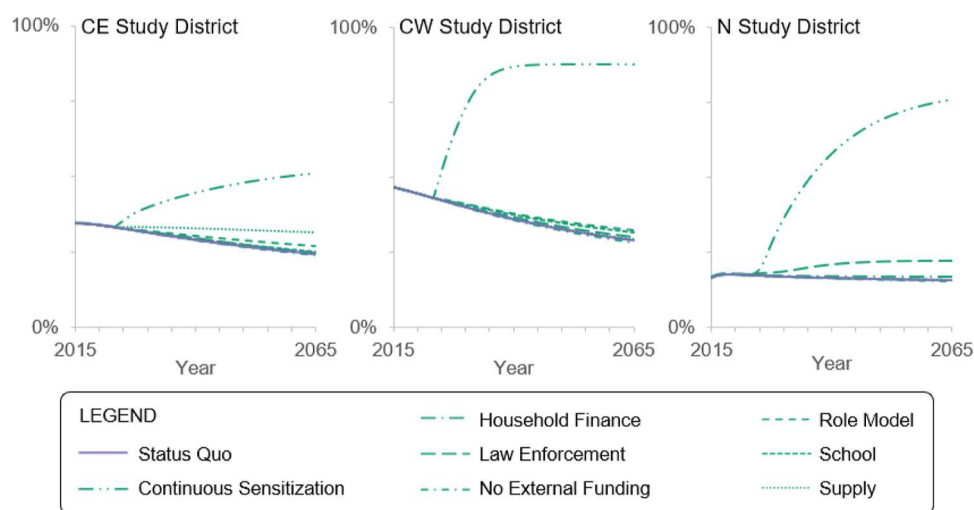


Figure 4. Results for improved sanitation coverage (basic and limited sanitation service levels) under different scenarios.

modeling insights, gained through rigorous application of the system dynamics method (which is, of course, limited by its own paradigmatic lens¹⁸).

When we began the study, we expected to construct different models for each of the three study districts. This followed a deeply held assumption that context should not be understated in complex systems. However, during the model building process, we realized that the models' components and their causal relationships were mostly the same and that any differences were captured by changes in contextual parameters. We must emphasize that this was true for our purpose (learning about system structure and high-level policy implications); models built for the purpose of detailed policy implementation would likely be different for each district. This realization led us to build a single simulation model that allowed for district-specific parametrization.

There were some differences among the study districts in the relative effects of the scenarios on improved sanitation coverage. For example, in Figure 4, which shows the scenario simulation results, the supply scenario caused more variation from the status quo in the central east study district than it did in the other study districts. This seems to be a consequence of improved latrine demand being greater than supply (in this case, the availability of trained sanitation service providers) in the central east study district, whereas supply is greater than demand in the other two districts. Similarly, the Law Enforcement scenario was more impactful for the northern study district, which can be traced to that district having a higher portion of households with no desire to construct a latrine (and therefore a lower perceived value of sanitation). However, in all cases, improving households' perceived value of sanitation through sensitizations (continuous sensitization scenario) influenced sanitation outcomes more than any other scenario.

Interestingly, removing external funding and resources (no external funding scenario) had only a minor impact on improved sanitation coverage in all of the study districts. This implies that the "leave no one behind" balancing loop is less influential than the other feedback loops in the model structure, with all else being equal. In our next simulations, we were interested in knowing what might happen if intervention conditions were applied for only a limited time.

Would the system reach a tipping point where the "leave no one behind" loop becomes dominant?

When we applied the continuous sensitization scenario for a duration of 5 years (a typical intervention time span), the improvements to sanitation coverage were not sustained (see

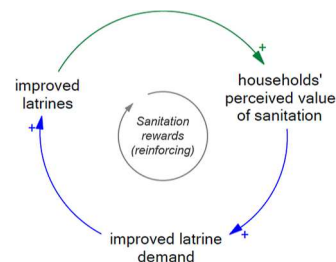


Figure 5. "Sanitation rewards" feedback loop. The green arrow (from improved latrines to households' perceived value of sanitation) indicates a new causal relationship which modifies the model structure.

Figure 6). This finding is reflected in real interventions, where most implementing organizations report an increase of latrines from baseline to endline, but postintervention monitoring reveals reversion to baseline conditions (e.g., ref 7). These results led us to conclude that without changing its structure or rules, the system seeks a relatively low equilibrium.

It follows that to shift the equilibrium upward (ideally to 100% improved sanitation), new feedback mechanisms that are not dependent on external resources must be added to the system. As discussed, households' perceived value of sanitation seems to be a major factor leading to improved sanitation in this context. According to our conceptual model, there is currently a gap between the attainment of improved latrines and households' perceived value of sanitation (ref 47 found a similar gap between latrine attainment and "emotional satisfaction" with one's sanitary practices). Therefore, we suggest that closing the loop between functional improved latrines and households' perceived value of sanitation could help provide the reinforcing feedback necessary to achieve and maintain universal sanitation. According to our simulations, this feedback should be provided directly to the decision maker such that the experience of owning (and using) an improved latrine (or other safely managed sanitation option) is

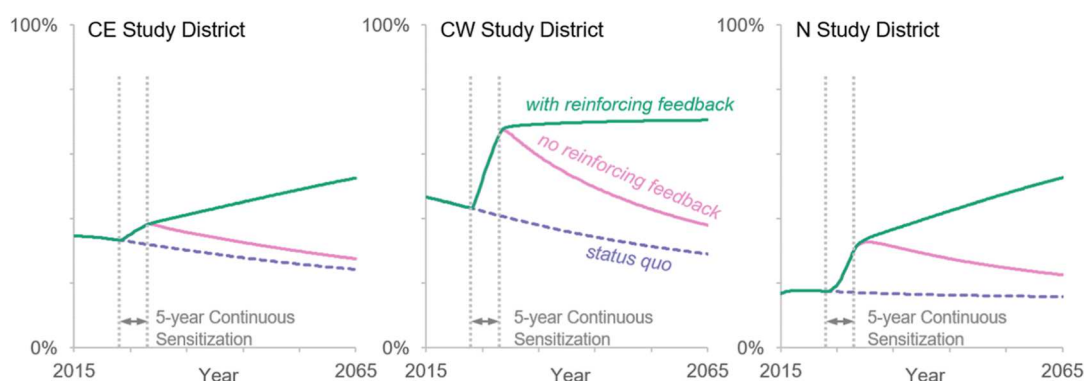


Figure 6. Simulation results for improved sanitation coverage showing the differences between the status quo and the 5 year continuous sensitization scenario with and without “sanitation rewards” reinforcing feedback.

rewarding to the user in the short term. This feedback loop, which we have named, “sanitation rewards,” is shown in Figure 5.

Closing the loop with direct feedback to latrine users is dependent on people having access to and using a latrine in the first place. As noted, real interventions are often successful at increasing the number of latrines in the short term. Therefore, we believe that “traditional,” adoption-oriented interventions are probably necessary to quickly achieve sanitation improvements in this context, but to be sustainable, they should incorporate a reinforcing feedback mechanism such as we have suggested. We do not recommend that the reward in this context be purely monetary. Others have found that the reinforcing action of sanitation subsidies is short-lived and not as cost-effective as social reinforcement through making a public commitment to improved sanitation, for example.^{7,48} Indeed, such social reinforcement may be a suitable mechanism for closing the “sanitation rewards” loop. As a household maintains an improved latrine after making a public commitment, such as reciting a pledge at monthly community meetings,⁴⁸ they might enjoy praise from community leaders or feelings of satisfaction which make the latrine seem more valuable to them. Furthermore, leadership development via programs such as “Civic Champions” in Cambodia,⁴⁹ could help motivate community leaders or local elected officials to deliver praise to individuals maintaining an improved, hygienic latrine. In the “Civic Champions” program, leaders whose communes met sanitation targets were eligible to share their strategy with other leaders and possibly win an award and cash prize. In terms of dynamics, the “sanitation rewards” feedback loop could constitute an intermediate phase that mitigates the long delays expected in more lasting feedback processes. Such long-term, slow-acting reinforcement might include increased comfort and familiarity with latrine use (i.e., habit-forming behavior), improved health outcomes, stronger governance institutions (including their capacity for monitoring, regulation, and enforcement), and reliable sanitation service markets.

Figure 6 shows the result of including a reinforcing feedback mechanism as part of a 5 year adoption intervention. The feedback mechanism is self-perpetuating, so it would continue after the end of the direct intervention. We have also assumed that the rate at which this feedback improves households’ perceived value of sanitation is the same as the background forgetting rate, a theoretical value that could be attributed to forgetting, migration, deaths/births, and negative experiences with or absence of any perceived benefits associated with

sanitation. The results were similar for all three study districts, showing that the achievements of short-term adoption-oriented interventions can be maintained, and in some cases improved upon, if a reinforcing feedback mechanism is also established.

While many of our findings are specific to the study topic and context, we believe that they support some general theories about intervening in complex systems which are now gaining recognition among practitioners in various disciplines (e.g., refs 50 and 51). Therefore, our study serves to demonstrate a modeling approach that “can elucidate the complex interdependencies of key environmental systems.”⁵² We believe that this approach could be widely adopted by those who hope to improve sanitation intervention and policy designs. Therefore, we conclude with the following recommendations: first, conceptualize sanitation systems in terms of their structure—the way that components are interrelated through feedback to produce observed behaviors. These dynamic hypotheses should be informed by system-level knowledge gathered (ideally) through participatory processes, such as group model building. Simulation modeling can help build confidence in dynamic hypotheses and allows for sensitivity and other quantitative analyses to explore influential factors and identify tipping points (if they exist). Finally, design simulation scenarios (or other experiments) to test and improve understanding about complexity in the context of sanitation. We hope that these steps will lead others to consider the whole “lifespan” of a policy or intervention (beyond the implementation period) including how intervention feedback loops can be designed and implemented to sustain outcomes long after external support is removed.

■ ASSOCIATED CONTENT

SI Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acs.est.3c09101>.

Document containing additional details on study context and methods (PDF)

Compressed folder containing SDM-Doc model documentation, including an .mdl file (ZIP)

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Notes

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