BMJ Global Health

Shifting the dynamics: implementation of locally driven, mixed-methods modelling to inform schistosomiasis control and elimination activities

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To cite: Fergus CA, Ozunga B, Okumu N, *et al*. Shifting the dynamics: implementation of locally driven, mixed-methods modelling to inform schistosomiasis control and elimination activities. *BMJ Global Health* 2022;**7**:e007113. doi:10.1136/bmjgh-2021-007113

Handling editor Seye Abimbola

► Additional supplemental material is published online only. To view, please visit the journal online (http://dx.doi.org/10.1136/bmjgh-2021-007113).

Received 7 August 2021
Accepted 3 January 2022

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ABSTRACT

Introduction The integration of more diverse perspectives into the development of evidence for decision-making has been elusive, despite years of rhetoric to the contrary. This has led to cycles of population-based health interventions which have not delivered the promised results. The WHO most recently set a target for schistosomiasis elimination by 2030 and called for cross-cutting approaches to be driven by endemic countries themselves. The extent to which elimination is feasible within the time frame has been a subject of debate.

Methods Systems maps were developed through participatory modelling activities with individuals working on schistosomiasis control and elimination activities from the village through national levels in Uganda. These maps were first synthesised, then used to frame the form and content of subsequent mathematical modelling activities, and finally explicitly informed model parameter specifications for simulations, using the open-source SCHISTOX model, driven by the participants.

Results Based on the outputs of the participatory modelling, the simulation activities centred around reductions in water contact. The results of the simulations showed that mass drug administration, at either the current or target levels of coverage, combined with water contact reduction activities, achieved morbidity control in high prevalence *Schistosoma mansoni* settings, while both morbidity control and elimination were achieved in high prevalence *S. haematobium* settings within the 10-year time period.

Conclusion The combination of participatory systems mapping and individual-based modelling was a rich strategy which explicitly integrated the perspectives of national and subnational policymakers and practitioners into the development of evidence. This strategy can serve as a method by which individuals who have not been traditionally included in modelling activities, and do not hold positions or work in traditional centres of power, may be heard and truly integrated into the development of evidence for decision-making in global health.

Key questions

What is already known?

- The elimination of schistosomiasis as a public health programme has been shown to be feasible, as evidenced by previous case studies and predictive modelling estimates.
- However, the continued prioritisation of mass drug administration, with the minimal integration and lack of widespread financial support for alternative interventions, is not supported by this evidence.
- Further, there remains a disconnect between the rhetoric of country-driven, locally based solutions to global health problems, which have been shown to significantly improve impacts, and the reality of its widespread implementation.

What are the new findings?

- In this study, we used participatory modelling to shape and inform mathematical modelling, demonstrating one of the possible strategies to integrate a wider range of perspectives in the form of individuals directly involved in the policy, oversight, and implementation of control and elimination activities within endemic countries.
- We conducted participatory systems mapping workshops with individuals at the village, district and national levels of the Uganda Ministry of Health, then used these outputs to select and inform the parameters of an open-source individual-based model.
- The results of this approach showed that achieving morbidity control and elimination was achievable within most recent time frame set forth by the WHO, once priority was given to complementary interventions.

What do the new findings imply?

- Incorporating the perspectives of individuals embedded in the biological and social systems of locations with endemic schistosomiasis has important, positive impacts on the development of evidence to support policy and practice.
- As has been suggested by previous evidence, and supported by this study, intervention strategies need to be tailored to local contexts, supported by a reorientation in the development of evidence for decision-making.

INTRODUCTION

As described by the WHO's Director of the Department of Neglected Tropical Diseases (NTDs), the newest strategy to control and eliminate NTDs by 2030 (the 'NTD Road Map to 2030')[1] was 'built on the principle of impact at country level through cross-cutting approaches, owned and driven by countries themselves, and augmented by coordinated support from partners'.[2] Similar comments have been made specifically about the NTD, schistosomiasis, for which the primary interventions are mass deworming activities, referred to as preventative chemotherapy (PC) or mass drug administration (MDA), which are the distributions of deworming medicines to populations or subpopulations in defined geographical areas without individual diagnosis. Policymakers and practitioners have described the need to move from a top-down approach focused solely on MDA to integrated and adaptive strategies which are responsive to specific settings and populations.[3–6] These discussions are supported by empirical evidence in countries where schistosomiasis elimination has occurred, yet none of which achieved success through mass deworming strategies alone.

In addition to the lack of effectiveness in achieving elimination, meta-analyses have shown that mass deworming interventions targeting schistosomiasis are largely ineffective at improving child health outcomes.[7 8] These results are complemented by modelling studies that have shown the current recommendations for MDA are not predicted to achieve the WHO targets of morbidity control or elimination as a public health problem within the specified timelines.[9 10] This is especially pronounced in high prevalence settings, where achieving targets with MDA alone is not likely unless the intervention coverage is increased to 85% in school-aged children (SAC) and 40% of individuals over the age of 15 years.[11] The practical implementation of such changes would be challenging given the current target of 75% SAC coverage remains elusive in most locations.[1] The inclusion of additional interventions, such as snail (vector) management and water sanitation and hygiene (WASH) activities, has been predicted to reach the targets within the time frame specified in the NTD Road Map to 2030,[9] yet remain as secondary or optional components to the MDA-focused agendas of many donors, policymakers and researchers. In addition, once the targets are reached, there remain uncertainties about how feasible it will be to maintain low prevalence levels in some areas without continued rounds of PC, potentially in perpetuity.[12]

This perpetuation of biomedical solutions to complex infectious disease problems delivered through vertical programmes, despite evidence favouring more holistic approaches, has been well documented and critiqued.[13 14] These interventions have been largely devised outside of the recipient localities and are often implemented without the genuine input from relevant public authorities and intended beneficiaries.[15] This is compounded by the disconnect between the development of evidence to justify and support intervention implementation and the actual evidence needs of policymakers and practitioners in endemic countries for decision-making regarding control and elimination activities.[16] Together these processes undermine the domestic ownership of health issues and solutions because they position the decision-making power around prioritisation, service delivery and evaluation largely outside of the countries themselves.[17 18] And, ultimately, this runs antithetical to the principles espoused in the most recent NTD Road Map to 2030.

To shift these dynamics, it is vital to integrate more diverse perspectives, particularly from those embedded within the endemic settings. Not only will this enhance country ownership, but will also improve the design, delivery, and, ultimately, the impact of interventions. Schistosomiasis as a complex disease problem is embedded in space-specific social, economic, biological and environmental systems. The dynamic relationships between these systems determine the prevalence of the disease and the effectiveness of interventions, which are not captured in linear theories of change or reductionist methods of evaluation. Individuals who themselves are embedded in these systems can provide critical insights as to these relationships and the potential impacts of interventions over time. Mass deworming activities, in particular, are often implemented with complementary components, such as WASH or nutrition activities—all of which influence each other to produce a summative effect different from that of the individual components.[19] In addition, population-based interventions generally should be viewed as dynamic, longitudinal processes, as interactions with local ecologies and social systems affect the interventions and intervention settings over time.[20 21] These features configure non-linear relationships, especially feedback loops and phase transitions, which are not accounted for in the prevalent deterministic, linear models of change.[20 22]

This study aimed to develop evidence for decision-making in response to the needs of policymakers and practitioners from the Uganda Ministry of Health (MoH), while incorporating the complexity of schistosomiasis transmission and control activities. This was accomplished by (1) capturing their perspectives on schistosomiasis transmission using qualitative participatory modelling, and (2) using the participatory modelling outputs to inform mathematical model simulations in response to the evidence needs. Participatory methods have been previously used to inform health policy, practice and evaluation, most notably in relation to non-communicable diseases[23] and accompanying risk factors,[24] but has not been linked explicitly to modelling work and the development of evidence for decision-making in this way or context. Similar variations of this protocol used for this study have been previously described in the context of energy policy[25] and ecosystem management,[26] but not implemented outside of higher income countries in the context of NTDs.

METHODS

Various types of participatory modelling have been used to generate shared conceptual depictions of complex health issues, following on from the prominent work on poverty reduction and development led by the World Bank and other research through the late 20th century, such as Robert Chambers' work on Participatory Rural Appraisal.[27] Systems mapping is a type of participatory modelling, used to elicit and quantify diverse perspectives from a variety of actors on causal relationships within complex systems. The process ends with a 'systems map', a diagram of explicit factors, causally linked to one another, which visually depicts a defined 'system' from the perspective of participating discussants[25]; examples of similar outputs include causal loop diagrams and stock-and-flow diagrams. More recently, systems mapping has been embraced by some working on computational modelling and simulation methods as a way to inform models with 'real-world' information vis-a-vis the outputs of 'purposeful learning processes for action that engage the implicit and explicit knowledge of stakeholders to create formalised and shared representations of reality'.[28] Depending on the aims and context, systems maps can be used to guide, inform, and even employed as the frameworks for simulations and other modelling activities. In health, systems maps have previously been used in calls for applying a systems epidemiology framework to schistosomiasis.[29] In this study, systems maps produced using the Participatory Systems Mapping (PSM) method with individuals working on schistosomiasis in Uganda framed the form and content of subsequent modelling activities and explicitly informed model parameter specifications.

Participants

Individuals working on schistosomiasis control and elimination activities from the national, district and village levels within the Ugandan health system were invited to participate in workshops in October of 2019. The aim was to implement a process which captured their perspectives and then incorporate these into the development of evidence for decision-making which was directly responsive to their needs. Thirty-three individuals from the national, district and village levels participated in two PSM workshops over 3 days. The participants were purposively invited to the workshop in consultation and coordination with the Uganda MoH Vector Control Division and the Uganda-UK Health Alliance. Individuals were selected from low, moderate and high transmission settings, with the aim of capturing diverse perspectives and encouraging discussions across transmission settings. Those individuals from the national level were from MoH departmental headquarters and two non-governmental organisations involved in schistosomiasis control activities. Individuals from the district level included district vector control officers and district health officers within the MoH organisational structure. Individuals from the village level were members of village health teams (VHTs), volunteer community health workers also organised within the MoH. One workshop with national-level and district-level representatives took place in Kampala, and the second workshop with members of VHTs took place in Jinja. Participants were reimbursed or provided with transportation, accommodation and sustenance to facilitate their participation.

PSM workshops

The workshops included presentations on the fundamentals of modelling and evidence related to schistosomiasis, as well as small and large group discussions on schistosomiasis control and elimination strategies and evaluation of the PSM outputs. In addition, participants were provided background on how systems maps could be used to define the parameters of simulation activities. The PSM exercises followed the process described by Barbrook-Johnson and Penn from the Centre for Evaluating Complexity Across the Nexus (CECAN).[25] After being provided with background and instructions on PSM, small groups of four to eight participants were formed based on health system level, to ease potential pressures of speaking up in the presence of workplace superiors.

The PSM was managed in each group by one or two facilitators and a note-taker. To begin the exercise, each group was given the prompt 'schistosomiasis transmission' and instructed to individually brainstorm factors which directly or indirectly impact transmission. These were then brought together and linked causally through group debate and consensus over course of a day. The systems maps were initially built using erasable paper, markers and sticky notes. Digitised versions of the systems maps were presented to the participants for validation, and the digital versions were corrected accordingly.

Subsequent large group discussions used the systems maps as tools to describe the impact of specific factors represented in the systems maps, and describe how interventions might be designed and implemented to influence key points in the system to drive down schistosomiasis transmission. The maps were also used as a point of departure to evaluate the potential causes for the lack of effectiveness of current interventions, in particular MDA, on producing long-term, sustained reductions in schistosomiasis transmission.

Generation of the aggregated systems map

To incorporate the group maps into a full systems map, the factors from each group were combined and standardised to a minimal extent (eg, 'children playing/swimming' and 'children playing in water' were standardised to 'playing/swimming') for a master list of factors described by the participants as directly or indirectly related to schistosomiasis transmission (see online supplemental materials 1). Each group map was then reimplemented with the standardised factor names as two-dimensional adjacency matrices, with cell values ($\alpha_{i,j}$) equal to +1 (positive relationship), −1 (negative relationship) or 0 (no relationship) from the row factor (i) to the column factor (j). Factors from the master list not included in a given group map were added to the corresponding adjacency matrix (with $\alpha_{i,j}$=0) as needed for a conformable set of matrices. Matrix addition was used to combine the four matrices, with the resultant $\alpha_{i,j}$ values (ranging from −4 to +4) representative of the generalised importance of each factor, captured by frequency with which each relationship was mentioned across the systems maps.

The full adjacency matrix was exported as a weighted edge list and projected as the full systems map. Structural analysis of the full map considered network centrality measures to identify the factors of greatest interest.[30] This method of network analysis was chosen a priori as part of the study protocol to reduce researcher bias in the identification of factors of interest, and also with the intention to use the same method in subsequent research comparing systems maps over time and between countries. These were considered along with the outcomes of the small and large group discussions to define the purpose of the subsequent model simulations and inform the model parameter specifications. Following the workshops, the participants provided feedback on the summaries of the activities and discussions to ensure that the notes accurately reflected the content, and verified the final digitised versions of the systems maps. Additional inputs from participants were included through individual discussions as the modelling process progressed, with respect to their time commitments through 2020.

Model and simulation overview

In terms of appropriate methods for incorporating complexity, individual-based modelling is able to accommodate the stochastic, non-linear, and dynamic interactions between humans and the environment in the transmission cycle of schistosomiasis. In addition, and of importance for the purposes of this study, it is scalable (from a village to a national setting), adaptable across contexts, flexible in the types of information that can be included and inclusive in the ways that outputs can be communicated. The SCHISTOX model employed in this study is an individual-based simulation model developed by Graham *et al*.[31] In addition to the suitability of its stochastic framework and inclusion of both *Schistosoma mansoni* and *S. haematobium* species, the SCHISTOX model has the distinct advantage in its development as an open-source repository on GitHub,[32] which can be run in Julia or through an R wrapper. This latter point is particularly important in that it allows for more straightforward communication with workshop participants, as they are able to see and work with the actual coding, when compared with other stochastic models of schistosomiasis transmission, which were reported as being seen by participants as 'black boxes'. Model parameters, categorised as human population, parasite population, transmission or control, can be explicitly specified based on a given context and available information. Given the prevalence of both *S. haematobium* and *S. mansoni* across Uganda, models were run to include the relevant parameter specifications adapted for both species. Parameters were defined by Graham *et al*'s SCHISTOX publication,[31] the SCHISTOX model documentation on GitHub (last accessed October 2021),[32] personal correspondence with the model developers and in consultation with workshop participants. As discussed next, the primary focus of the simulations presented here was to observe how changes in the population water contact parameter would impact the prevalence, with specific reference to the WHO target timelines, while holding the other initialisation parameter values constant. All parameter specifications used in this study can be found in online supplemental materials 2.

To initialise the simulations, each species-specific model was run for 100 years under high prevalence scenarios to establish epidemiological equilibrium within the population. The aim of the simulations followed the results of the PSM workshops and subsequent discussions with participants. In particular, participants were interested in the potential impacts of limiting water contact and had suggested a variety of context-specific and place-specific interventions. Some of these interventions included providing gum boots to rice farmers and fisher-folk, clothes washing stations and bathing shelters (see online supplemental materials 4, theme 2 for additional details from participants-related water contact). Given the aim to provide generalised guidance to these diverse situations, exploratory age-specific water contact was simulated over a series of proportional reductions which could then be applied in local contexts and decision-makers to scale preferred interventions.

To provide guidance on the potential impact of intervention combinations, four scenarios were considered in high prevalence *S. mansoni* and *S. haematobium* settings. Reduction in water contact was considered alongside MDA implementation. MDA coverage for SAC was simulated at two levels in accordance with the current WHO and national guidelines: (1) the most recent reported median coverage for high prevalence districts (46%, range),[33] and (2) the recommended target coverage of 75%.[1] The reported median coverage for high prevalence districts in Uganda was selected to provide a relevant reference point, relative to the recommended target coverage, for district and subdistrict decision-makers. The simulations were run for 10 years in the SCHISTOX R interface.

Patient and public involvement

There were no funds or time available for patient or public involvement in this study. Additional research based on this study involving individuals with schistosomiasis is being developed. However, we are cognisant of the effects of the ongoing COVID-19 pandemic in the areas where we work and are putting our efforts into the pressing needs of the health workers and patients ahead of a research agenda.

RESULTS

The systems maps produced through PSM presented complex, dynamic perspectives on the transmission of schistosomiasis across Uganda. The participants

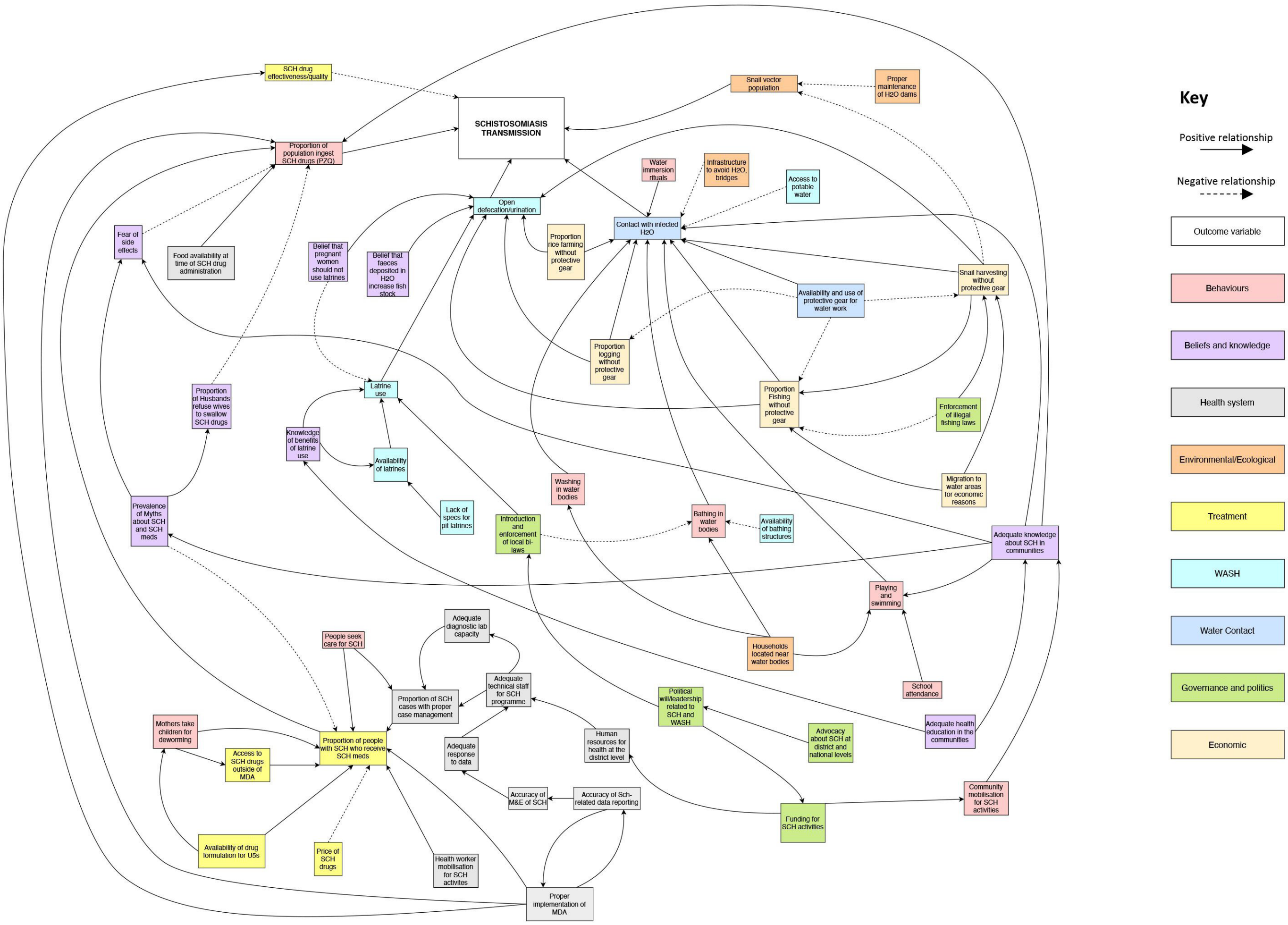

Figure 1 Aggregate systems map. M&E, monitoring and evaluation activities; MDA, mass drug administration; PZQ, praziquantel; SCH, schistosomiasis; U5s, children aged less than five years; WASH, Water Sanitation and Hygiene activities.

identified key points of potential intervention as centred around water contact from economic, household, hygiene and leisure activities. The aggregate systems map (figure 1) shows five factors directly influencing schistosomiasis transmission: open defecation/urination, ingestion of the schistosomiasis drug praziquantel, quality/standard of schistosomiasis drugs (drug efficacy), population of snail vectors and contact with infested water. The factors identified as directly or indirectly effecting schistosomiasis transmission were across eight categories: individual behaviours, beliefs and knowledge, health system components and activities, environmental/ecological, schistosomiasis treatment/drugs, WASH, water contact activities and governance/politics. The small group maps can be found in online supplemental materials 3. The key discussion points which emerged from the small and large group discussions are summarised in table 1 and online supplemental materials 4.

To further analyse the structure of the aggregate systems map, network centrality metrics were determined for each of the factors. In line with the small and large group discussions, the factors with the highest degree centrality, that is, those with the highest number of incident links from and to other factors, were 'contact with infested water' and 'open defecation and urination' (see online supplemental materials 5 for all network centrality metrics). This suggests that these are vital intervention points in the system of schistosomiasis transmission from the perspectives of the workshop participants.

As discussed above, following on from the outputs of the participatory modelling and analysis of the aggregate map, the simulation activities centred around reductions in water contact. As an exploratory step, simulated reductions in the age-specific water contact in relation to the initialisation parameters were tested. Results showed that decreasing contact with infected water by 75% across all ages in high *S. mansoni* prevalence settings, while holding all else equal, achieved morbidity control within 20 years and achieved elimination as a public health problem within 30 years. In high *S. haematobium* settings, water contact reductions of 75% achieved morbidity control within 15 years and elimination within 20 years (all of the water contact exploratory simulation results can be found in online supplemental materials 6).

Further simulations were used to compare the impact of water contact reductions with current and target MDA coverage levels on the prevalence of schistosomiasis, individually and in combination (figure 2). The simulation

Table 1 Key discussion points and examples from Participatory Systems Mapping workshop and follow-up

No	Key discussion point	Specific examples
1	Water contact is an especially important transmission/ potential control point which allows for substantial flexibility in the design of interventions and control of implementation components at the local level.	Specific control points were economic activities (fishing, rice farming and snail harvesting), household activities (washing, fetching water) and hygiene activities (bathing, latrine use).
2	The only group level focused on MDA implementation was comprised of members of village health teams (VHTs); the district-level and national-level groups mentioned the intervention, but not in detail.	As the group directly responsible for MDA implementation, the VHTs detailed material support (bags to carry medicines, fuel, salaries) as factors influencing MDA implementation.
3	Individuals from all groups discussed the lack of available treatment in communities outside of MDA implementation periods.	The lack of treatment availability in health facilities leads to the inability to provide proper case management with the absence of drugs in lower level health facilities or with VHTs.
4	Communication related to schistosomiasis transmission and interventions needs to be improved between the national, district and village levels.	There was a disconnect in the dissemination of updated, relevant and useful materials from the national to the subnational levels, specifically these concerns were the need for translation into local languages and the provision of hard copy formats.
5	The system for collecting data related to schistosomiasis is inefficient and ineffective for routine use and facilitating responses.	Data collection and feedback are a patchwork of reliability and completely dependent on the individual data collector at the community level and the aggregator at the district level.

MDA, mass drug administration; MDA, mass drug administration (preventative chemotherapy).

results showed that employing MDA for SAC as the sole intervention, at both the current median coverage level in high prevalence districts in Uganda (46%), and the policy-recommended target of 75% coverage, did not achieve either morbidity control or elimination within the 10-year time period. The results showed that combining

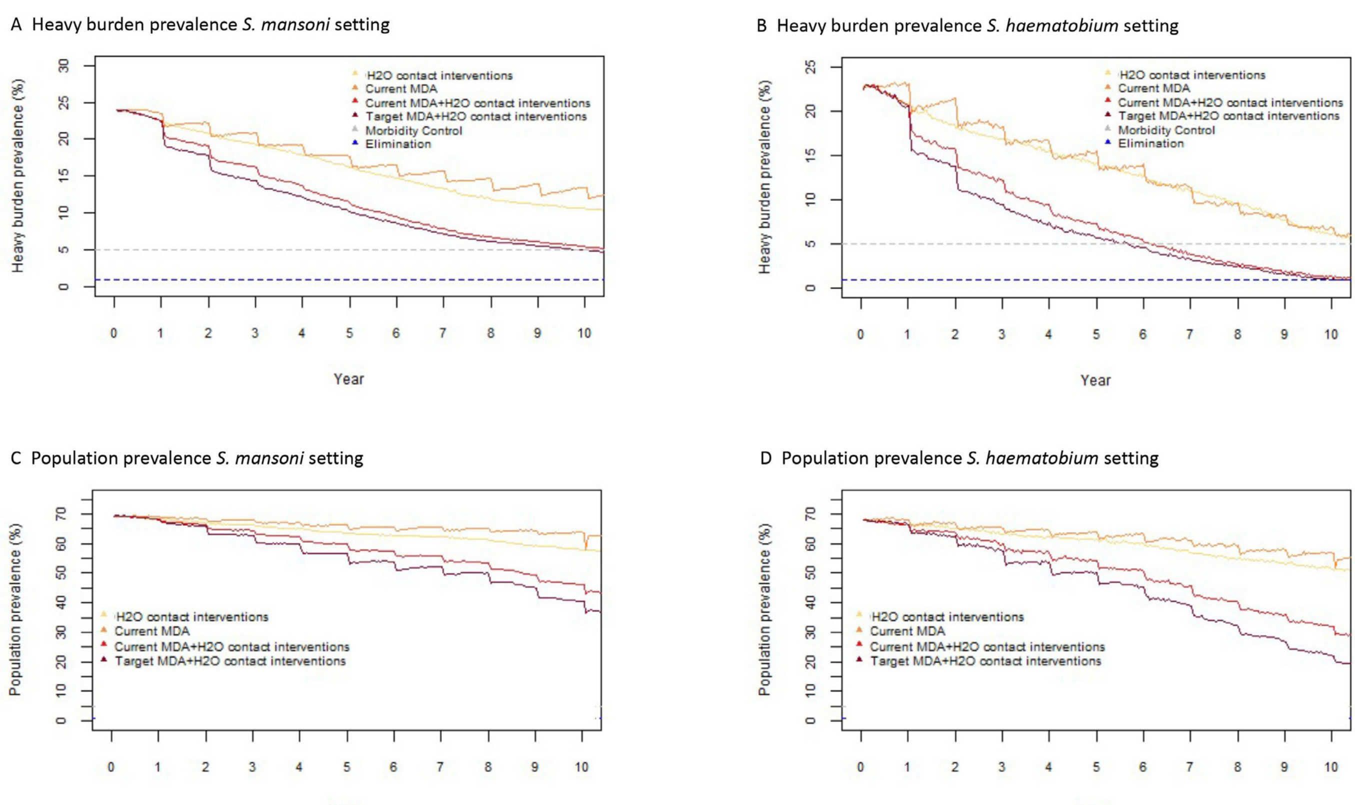

Figure 2 A-D. MDA and water contact reduction simulation results. Note: H_2O contact interventions, implementation of water contact reduction interventions to decrease contact by 75%; current MDA, most recent reported median coverage of school-aged children (SAC) for high prevalence districts in Uganda (46%); target MDA, recommended target coverage of SAC in high prevalence districts of 75%; these results were not adjusted for diagnostic sensitivity. MDA, mass drug administration.

water contact reduction interventions at 75% with the current (46%) or target (75%) MDA coverage reached the most recent WHO's NTD Road Map to 2030 targets of morbidity control and elimination in both *S. mansoni* and *S. haematobium* settings within 10 years. While the simulations indicated that morbidity control and elimination could be achieved, as these indicators pertain to high intensity infections, it should be noted that population prevalence did not achieve 5% or 1% targets in settings with either species within 10 years (figure 2).

DISCUSSION

This study used PSM to elicit and depict the perspectives of Ugandan policymakers and practitioners on factors related to schistosomiasis transmission and interventions. Focus group discussions and follow-up interviews provided additional information and insights as to their evidence needs and guided the subsequent modelling activities. These outputs framed individual-based modelling simulations and were incorporated into the model parameter specifications. Simulations were used to predict the impacts of water contact reductions in communities of high *S. haematobium* and *S. mansoni* prevalence settings. The combination of PSM and individual-based modelling was a rich strategy which explicitly integrated the perspectives of national and subnational policymakers and practitioners into the development of evidence for decision-making related to schistosomiasis control and elimination activities.

The visualisations of the schistosomiasis transmission system were produced by national-level, district-level, and village-level policymakers and practitioners involved in schistosomiasis control and elimination activities. The systems maps indicated causal effects and the directionality of these effects (positive or negative) by linking factors where relationships were perceived to exist. The digitised versions of the maps served as depersonalised expressions of consensus by small groups that facilitated conversations in the large group about difficult topics, related in particular to resources, data and the lack of sustained reductions in prevalence after years of deworming interventions. These discussions may not have otherwise taken place openly given the social dynamics between district-level and national-level participants. Feedback from participants indicated that they hoped to use the systems maps to advocate for resources they deemed necessary from within the Uganda and among international donors and aid agencies, as the maps were viewed as leverage in a system of top-down decision-making around schistosomiasis control activities. PSM encouraged critical thinking and provided the space to develop potential solutions based on lived and professional experiences. From the systems maps, it was clear that participants at the national, district and village levels were most focused on factors that increase or decrease infested water contact, a key intervention point in the schistosomiasis transmission cycle. This perspective was used to guide the model simulation activities.

The SCHISTOX individual-based model by Graham *et al*[31] was employed to simulate the impacts of age-specific reductions in water contact under various scenarios. The results showed that employing MDA alone, at either the current or target levels of SAC coverage, did not result in achieving the most recent NTD Road Map to 2030 targets of morbidity control or elimination in high prevalence settings within 10 years. However, when combined with water contact reduction activities, morbidity control was reached in *S. mansoni* settings and morbidity control and elimination were achieved in *S. haematobium* settings within the same 10-year time period. These outcomes were modelled in the context of high prevalence levels and may not be generalisable to low or moderate prevalence settings.

There were several important insights from this study relevant to the broader context of the NTD Road Map to 2030 and the global strategies for achieving schistosomiasis morbidity control and elimination. The PSM supported critiques about mass deworming strategies as vertical, top-down interventions.[3 4] The simulations provided further evidence that MDA alone will not achieve the prevalence reduction targets.[9 10] Individuals from VHTs were the only group to specifically discuss the implementation of MDA in relation to schistosomiasis transmission, most likely because they were directly responsible for carrying out these activities. The lack of access to treatment for routine care within the communities, leading to the inability to provide adequate case management, was an important gap highlighted in the context discussions about MDA.

Interventions to reduce exposure to infected water were not included in the WHO's NTD Road Map to 2030, despite being the reported driver to elimination of schistosomiasis in previous case studies in the same document. In this study, water contact was described as the key potential intervention point in the schistosomiasis transmission cycle by participants and reduction in water contact was shown in simulations to be an important component leading to decreased prevalence and eventual elimination. Previous empirical work by Knopp *et al* showed that behavioural and educational interventions were not as effective at reducing schistosomiasis prevalence as MDA alone or as integrated components,[34] although, as has been discussed elsewhere,[4] the integrated components may not have been implemented widely enough to generalise the findings.

There is clearly still a need to better understand the feasibility and costs of water contact reduction interventions. In most places with a high prevalence of schistosomiasis infections, contact with local water bodies underpins the social, economic and hygiene activities of daily life. Therefore, any adaptations to these activities would need to be developed and led from within communities in order to achieve meaningful reductions in water contact. The degree to which this is feasible, and the extent of the impact, is entirely context specific and dependent on holistic approaches to funding and implementation. In addition, a bigger push toward community-wide MDA in all relevant high-prevalence areas, improvements in diagnostics, the prospects of a vaccine and a host of other innovative technologies will undoubtedly play a role in moving toward the elimination of schistosomiasis as a public health problem.

It is also important to acknowledge the challenges with implementing participatory modelling and the potential issues with its outputs. Clearly the biggest limitation of the work presented here is that participatory modelling activities are very resource intensive, both in time and money. Prior to the implementation of the activities, it requires relationship building to foster credibility and buy-in from participants. In terms of outputs, fundamentally, the systems maps are abstractions of reality. These are negotiated representations of individual perspectives which do not 'objectively' nor entirely capture the system which results in schistosomiasis transmission. In this way, actually, the outputs of participatory modelling are akin to the outputs of mathematical modelling: both are inherently biased by the composition of individuals whose inputs drive and shape these processes. One of the broader aims of this work was to explore how we might explicitly use these biases to allow for locally fostered approaches to evidence for decision-making.

CONCLUSION

The WHO's NTD Road Map to 2030 calls for a country-led process supported by partners. If this is meant beyond rhetoric, partner organisations need to engage with policymakers and practitioners in endemic countries, not only as the recipients of evidence for decision-making or facilitators of interventions produced outside the communities, but as individuals capable of driving these processes. This study demonstrates one of many possible strategies to integrate a wider range of perspectives in the form of individuals directly involved in the policy, oversight, and implementation of schistosomiasis control and elimination strategies within endemic countries. Inclusivity and the flexibility to allow innovation to be driven by a more diverse set of voices and experiences will push the sustainable reduction in the burden of schistosomiasis by 2030.

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Acknowledgements We would like to acknowledge Dr Moses Adriko (Uganda Ministry of Health Vector Control Division) and Dr Georgina Pearson (London School of Economics and Political Science; Queen Margaret University, Edinburgh) for their assistance in conducting the participatory workshops. We would like to thank Dr Elizabeth Storer (London School of Economics and Political Science) for her input and thoughtful insights through the writing process. We would also like to thank Dr Tiziana Leone and the participants of LSE's Global Health Initiative Reading Group for comments on earlier iterations of this manuscript. We thank the health workers, practitioners and policymakers working in Uganda who participated in the workshops, provided feedback throughout the processes described in this paper and continue to work with us while balancing their responsibilities through the COVID-19 pandemic. Finally, we thank Dr Matthew Graham and Dr Diepreye Ayabina from University of Oxford's Big Data Institute for their invaluable assistance and insights on working through their SCHISTOX model. Their willingness to provide support to the end of creating a truly open-source individual-based model reflects the best we can hope for in the future of scientific research.

Contributors CF, MP, SK, BO, NO and TA implemented the study and provided interpretations of the data. CF guided the conceptualisation and investigation, wrote the first draft of the article, and guided the writing, review, and editing. All authors contributed to drafting the work or revising it critically for important intellectual content, and all authors have read and approved the final version. All authors agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. CF accepts full responsibility as guarantor of the overall content, including the finished work, the conduct of the study, access to the data, and control over the decision to publish.

Funding This study was funded by Research England's Bloomsbury Science, Engineering, and Technology (SET) grant programme (Localised Evidence and Decision-making Project Reference BSA04; Award Reference CCF17-7779).

Disclaimer The funder of the study had no role in the study design, data collection, data analysis, data interpretation or writing of the report. The authors had full access to all the data in the study and accept responsibility for the decision to submit for publication.

Competing interests None declared.

Patient consent for publication Not required.

Ethics approval This study involves human participants and ethical clearance and permission for the relevant components of this study were granted from the London School of Economics and Political Science Research Ethics Committee (reference number 000914) and the Uganda National Council for Science and Technology (research registration number HS1285ES). Written informed consent was obtained from all workshop participants.

Provenance and peer review Not commissioned; externally peer reviewed.

Data availability statement All data relevant to the study are included in the article, uploaded as supplemental information, or available upon reasonable request.

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Shifting the Dynamics: Integration of participatory and mathematical modelling to inform schistosomiasis control and elimination activities

Supplementary Materials

Section 1. Participatory modelling outputs

Table S1. Participatory systems mapping full list of factors and standardisations

Factors from group systems maps (PSM exercise)	**Group map**	**Standardised factor**	**Factor Type**
Bachelors or unmarried bathing in contaminated water	VHT	Bathing in water bodies	Behaviours
Bathing in natural water sources	National	Bathing in water bodies	Behaviours
Bathing in water	District1	Bathing in water bodies	Behaviours
Belief that lake/river water is pure and cleansing	National	Water immersion rituals	Behaviours
Children playing in water	District1	Playing and swimming	Behaviours
Children playing/swimming	District2	Playing and swimming	Behaviours
Children playing/swimming in contaminated water	VHT	Playing and swimming	Behaviours
Community mobilisation to participate in health related issues	District2	Community mobilisation for SCH activities	Behaviours
Compliance to pzq	District1	Proportion of population ingest SCH drugs (PZQ)	Behaviours
Going for stool examination	District1	People seek care for SCH	Behaviours
Leisure activities/swimming	National	Playing and swimming	Behaviours
MDA coverage (people taking pills)	National	Proportion of population ingest SCH drugs (PZQ)	Behaviours
Mothers take children for deworming	VHT	Mothers take children for deworming	Behaviours
People seek care for sch symptoms	District2	People seek care for SCH	Behaviours
People seek consultation for sch symptoms	VHT	People seek care for SCH	Behaviours
People take sch drugs	VHT	Proportion of population ingest SCH drugs (PZQ)	Behaviours
People taking PZQ	National	Proportion of population ingest SCH drugs (PZQ)	Behaviours
Refugees or migrants bathing in contaminated water	VHT	Bathing in water bodies	Behaviours
School attendance	VHT	School attendance	Behaviours
Taking sch tx	District1	Proportion of population ingest SCH drugs (PZQ)	Behaviours
Uptake of sch meds	District2	Proportion of population ingest SCH drugs (PZQ)	Behaviours
Washing in natural water sources	National	Washing in water bodies	Behaviours
Water immersion initiation rituals, including immersive baptism	National	Water immersion rituals	Behaviours
Adequate health edu about sch	District1	Adequate knowledge about SCH in communities	Beliefs and Knowledge
Adequate health education	National	Adequate health education in the communities	Beliefs and Knowledge
Adequate knowledge on sch transmission	District1	Adequate knowledge about SCH in communities	Beliefs and Knowledge

Adequate sch knowledge in the community	VHT	Adequate knowledge about SCH in communities	Beliefs and Knowledge
Attitude about taking the sch meds	District1	Fear of side effects	Beliefs and Knowledge
Awareness about sch in communities	District1	Adequate knowledge about SCH in communities	Beliefs and Knowledge
Belief that feces deposited in the water will increase fish catch	National	Belief that faeces deposited in H2O increase fish stock	Beliefs and Knowledge
Belief that pregnant women should not use latrine	National	Belief that pregnant women should not use latrines	Beliefs and Knowledge
Cultural beliefs about outdoor defecation - esp regarding pregnant women	District2	Belief that pregnant women should not use latrines	Beliefs and Knowledge
Fear of side effects	District1	Fear of side effects	Beliefs and Knowledge
Husbands refuse wives to swallow meds	District1	Proportion of Husbands refuse wives to swallow SCH drugs	Beliefs and Knowledge
Incorrect myths about sch or sch meds	VHT	Prevalence of Myths about SCH and SCH meds	Beliefs and Knowledge
Knowledge about sch in the community	District2	Adequate knowledge about SCH in communities	Beliefs and Knowledge
Knowledge of benefits of latrine use	National	Knowledge of benefits of latrine use	Beliefs and Knowledge
Latrine beliefs (pregnant woman loses child)	District1	Belief that pregnant women should not use latrines	Beliefs and Knowledge
Religious sector dont believe in modern meds	District1	Prevalence of Myths about SCH and SCH meds	Beliefs and Knowledge
Sch education for VHTs and religious leaders	VHT	Adequate knowledge about SCH in communities	Beliefs and Knowledge
Fishing activities	VHT	Proportion Fishing without protective gear	Economic
Fishing in infested waters without protective gear	National	Proportion Fishing without protective gear	Economic
Fishing without protective gear	District2	Proportion Fishing without protective gear	Economic
Full time boat use for economic activities	National	Proportion Fishing without protective gear	Economic
Harvesting snails	District1	Snail harvesting without protective gear	Economic
Logging without protective gear	National	Proportion logging without protective gear	Economic
Migration to district for economic purposes	District2	Migration to district for economic purposes	Economic
Mongering without protective gear	District2	Proportion Fishing without protective gear	Economic
Rice farming activities	VHT	Proportion rice farming without protective gear	Economic
Rice growing/harvesting without protective gear	National	Proportion rice farming without protective gear	Economic
Snail harvesting as an economic activity	National	Snail harvesting without protective gear	Economic
Snail harvesting without protective gear	District2	Snail harvesting without protective gear	Economic
Value/price of snail shells	District1	Snail harvesting without protective gear	Economic
Availability of snails that are infected	National	Snail vector population	Environmental/Ecological
Presence of snail vectors	District2	Snail vector population	Environmental/Ecological

Adequate infrastructure for avoiding water - esp bridges	National	Infrastructure to avoid H2O, bridges	Environmental/Ecological
Adequate infrastructure/bridges for crossing water	District1	Infrastructure to avoid H2O, bridges	Environmental/Ecological
Living near water bodies	National	Households located near water bodies	Environmental/Ecological
Proper maintenance of water dams	National	Proper maintenance of H2O dams	Environmental/Ecological
Advocacy about sch at the district and national level	District2	Advocacy about SCH at the district and national level	Governance and Politics
Crackdown on illegal fishing	National	Enforcement of illegal fishing laws	Governance and Politics
Funding for sch activities	District2	Funding for SCH activities	Governance and Politics
Introduction and Enforcement of local bi-laws	VHT	Introduction and enforcement of local bi-laws	Governance and Politics
Political will to deal with sch at the LC1-5 level	District2	Political will/leadership related to SCH and WASH	Governance and Politics
Political will/leadership	VHT	Political will/leadership related to SCH and WASH	Governance and Politics
Presence and Enforcement of community bylaws	District2	Introduction and enforcement of local bi-laws	Governance and Politics
Private sector support	District2	Funding for SCH activities	Governance and Politics
Access of VHTs to fisher folk areas	District1	Proper implementation of MDA	Health System
Accurate data on sch	District1	Accuracy of SCH-related data reporting	Health System
Adequate and responsive health system surveillance system	District2	Adequate response to data	Health System
Adequate diagnostic/lab capacity	District1	Adequate diagnostic/lab capacity	Health System
Adequate logistics (time and transport) for drug distribution	District1	Proper implementation of MDA	Health System
Adequate tech staff for sch programme	District1	Proper implementation of MDA	Health System
Advocacy and mobilization within the districts	National	Health worker mobilisation for SCH activities	Health System
Appropriate quantity of PZQ for MDA	District1	Proper implementation of MDA	Health System
Available transport to sub county and parish	VHT	Proper implementation of MDA	Health System
Available transport to the district store	VHT	Proper implementation of MDA	Health System
Community acceptance of VHTs	District1	Proper implementation of MDA	Health System
Correct/adequate training for administering tx (during mda)	VHT	Proper implementation of MDA	Health System
Delays in funding and meds for MDA	District1	Proper implementation of MDA	Health System
Diagnostic capacity at health facilities - lab/clinician skills and equipment	District2	Adequate diagnostic/lab capacity	Health System
Drug stock at centre	VHT	Proper implementation of MDA	Health System
Drug stock at district store	VHT	Proper implementation of MDA	Health System
Falsification of data	District1	Accuracy of SCH-related data reporting	Health System

Food availability at time of mda or in health facilities to take w meds	District2	Food availability at time of SCH drug administration	Health System
Human resources for health at the district level	District2	Human resources for health at the district level	Health System
Irregular MDA	District1	Proper implementation of MDA	Health System
M&E related control efforts related to sch	District2	Accuracy of M&E of SCH	Health System
No dose poles or weight scales	VHT	Proper implementation of MDA	Health System
Pressure from center (national level) and donors	District1	Proper implementation of MDA	Health System
Proper case management	District2	Proportion of SCH cases with proper case management	Health System
Respect for VHT in the community	VHT	Proper implementation of MDA	Health System
Timely and accurate sch surveillance data	District2	Accuracy of SCH-related data reporting	Health System
Unmanaged sch cases (human reservoir)	District2	Proportion of SCH cases with proper case management	Health System
VHT giving the wrong dose (too low)	VHT	Proper implementation of MDA	Health System
VHT is able to pick drugs from the parish level	VHT	Proper implementation of MDA	Health System
VHT motivation	VHT	Proper implementation of MDA	Health System
VHT salary	VHT	Proper implementation of MDA	Health System
VHTs find people at home during MDA	VHT	Proper implementation of MDA	Health System
VHTs have adequate storage for drugs	VHT	Proper implementation of MDA	Health System
VHTs have adequate transport	VHT	Proper implementation of MDA	Health System
VHTs have carrying bags for drugs	VHT	Proper implementation of MDA	Health System
VHTs have stock of drugs	VHT	Proper implementation of MDA	Health System
VHTs have time to distribute drugs during MDA	VHT	Proper implementation of MDA	Health System
VHTs reach people's homes during MDA	VHT	Proper implementation of MDA	Health System
Schistosomiasis transmission	District1	Schistosomiasis transmission	Outcome
Schistosomiasis transmission	District2	Schistosomiasis transmission	Outcome
Schistosomiasis transmission	National	Schistosomiasis transmission	Outcome
Schistosomiasis transmission	VHT	Schistosomiasis transmission	Outcome
Access to sch meds	District2	Access to SCH drugs outside of MDA	Treatment
Availability of PZQ in health facilities	District2	Access to SCH drugs outside of MDA	Treatment
Availability of sch tx for U5s	District1	Availability of drug formulation for U5s	Treatment
Drug formulation for U5s	District2	Availability of drug formulation for U5s	Treatment
Effectiveness of quality or standard of drugs	VHT	SCH drug effectiveness/quality	Treatment
Missing PZQ	National	Access to SCH drugs outside of MDA	Treatment
Price of PZQ	District2	Price of SCH drugs	Treatment

PZQ is not considered an essential drug	District2	Access to SCH drugs outside of MDA	Treatment
Sch drug coverage	District1	Proportion of population ingest SCH drugs (PZQ)	Treatment
Sch drugs available at health facilities	VHT	Access to SCH drugs outside of MDA	Treatment
U5s taking sch meds	District1	Availability of drug formulation for U5s	Treatment
Access to potable water	District2	Access to potable water	WASH
Availability of bathing shelters	VHT	Availability of bathing shelters	WASH
Availability of boreholes	District1	Availability of latrines	WASH
Availability of latrines	District1	Availability of latrines	WASH
Availability of pit latrines	District2	Availability of latrines	WASH
Availability of potable water	VHT	Access to potable water	WASH
Availability of potable water	District1	Access to potable water	WASH
Cannot dig minimum 15' requirement for latrine (time, money, soil type)	VHT	Lack specs for pit latrines	WASH
Lack of boreholes	VHT	Availability of latrines	WASH
Latrine availability	National	Availability of latrines	WASH
Latrine usage	District1	Latrine use	WASH
Latrine use	National	Latrine use	WASH
Open defecating in water/stream	District1	Open defecation/urination	WASH
Open defecation	District2	Open defecation/urination	WASH
Open defecation in water	VHT	Open defecation/urination	WASH
Open urination/defecation into water	National	Open defecation/urination	WASH
People obtain water from open source	VHT	Access to potable water	WASH
Poor texture for building pit latrines	District2	Lack specs for pit latrines	WASH
Poor texture of soil at landing sites to dig latrines	District1	Lack specs for pit latrines	WASH
toilet use	District2	Latrine use	WASH
Availability and use of gum boots	VHT	Availability and use of protective gear for water work	Water Contact
Availability and use of protective gear - gum boots, gloves, overalls	National	Availability and use of protective gear for water work	Water Contact
Availability of protective gear for work in water	District1	Availability and use of protective gear for water work	Water Contact
Contact with infected water	District1	Contact with infested H2O	Water Contact
Contact with infested waters	National	Contact with infested H2O	Water Contact
Enter contaminated water	VHT	Contact with infested H2O	Water Contact
Exposure to infested water	District2	Contact with infested H2O	Water Contact
Fisher folk not using protective gear	District1	Availability and use of protective gear for water work	Water Contact

Rice and yam farmers not using protective gear	District1	Availability and use of protective gear for water work	Water Contact
Use of personal protective gear	District2	Availability and use of protective gear for water work	Water Contact

Section 2. Mathematical modelling inputs

The primary purpose of the simulation results presented in this paper was to observe how variations (decreases in particular) in the population water contact parameter would impact the prevalence, while holding the other initialisation parameter values constant. The parameters were informed by four sources: (1) Graham et al's SCHISTOX publication[1], (2) the SCHISTOX model documentation on GitHub[2], (3) personal correspondence with the model developers, and (4) in consultation with workshop participants. Consultation with the workshop participants included written and verbal communication, both during the workshop and after the workshop as the parameters were specified. These communications continued through July 2021, and are ongoing as additional components of the project continue. In some cases, participants agreed that a value described in the SCHISTOX parameterisation documentation adequately reflected their contexts for the purposes of the simulation. In others cases, individual input, followed by group negotiation and consensus, determined the input value. All of the parameters were put up for discussion and confirmation by the participants, though only the ones which generated comments, and the extent of the input, are noted in the Table S2 below.

Table S2. Parameter specifications

Parameter	**Initial value/specification**	**Source**
N (population)	750	Input from workshop participants on the average most relevant population size
Time step	10	Parameterization documentation[2]
N communities	1	Parameterization documentation[2] and input from workshop participants
Density dependent fecundity	0.0007 (*S. mansoni)*; 0.0006 (*S. haematobium)*	Parameterization documentation[2] and personal correspondence with the model developers
Average worm lifespan	5.7 years (*S. mansoni)*; 4 years for (*S. haematobium)*	Graham et al's SCHISTOX publication[1]

[1] Graham M, Ayabina D, Lucas TCD, *et al.* SCHISTOX: An individual based model for the epidemiology and control of schistosomiasis. *Infectious Disease Modelling* 2021

[2] Graham M. Schistoxpkg.jl. 2021 https://github.com/mattg3004/Schistoxpkg.jl. (last accessed October 2021)

Maximum age in the population (years)	100	Confirmed by workshop participants as the most appropriate for their purposes
Miracidia maturity	24 (*S. mansoni)*; 21 (*S. haemotobium)*	Graham et al's SCHISTOX publication[1] and parameterization documentation[2]
Contact rate	0.1	Parameterization documentation[2] and personal correspondence with the model developers
Max fecundity	50	Parameterization documentation[2] and personal correspondence with the model developers; the max fecundity and max fecundity contact rate product (below) were set based on an investigation into the system behaviour in varying these parameters for the model simulation to reach equilibrium at a high population prevalence (>50)
Max fecundity contact rate product	1/15	Parameterization documentation[2] and personal correspondence with the model developers; the max fecundity and max fecundity contact rate product (above) were set based on an investigation into the system behaviour in varying these parameters for the model simulation to reach equilibrium at a high population prevalence (>50)
Age contact rates	c(0.0998, 0.4563, 0.4424, 0.0015)	Parameterization documentation[2] and personal correspondence with the model developers; these rates are normalised to 1 across the array
Ages for contacts	c(4, 9, 15, 100)	Parameterization documentation[2] and confirmed by workshop participants as the most appropriate for their purposes
MDA adherence	0.9	Parameterization documentation[2] and confirmed by workshop participants as adequately reflecting their contexts in general; although it should be noted that the village-level participants were

		especially interested in the impacts of varying this parameter and that work is ongoing
MDA access	0.9	Parameterization documentation[2] and confirmed by workshop participants as adequately reflecting their contexts in general; as with MDA adherence (above), while it was agreed that this parameter would be kept defined as in the parameterization documentation for the purposes of this simulation, the village-level participants were particularly interested in observing the impacts of varying this parameter
Factor for altering the contact rate for females	1	Parameterization documentation[2]
Factor for altering the contact rate for males	1	Parameterization documentation[2]
Proportion of cercariae which are able to infect humans	1	Graham et al's SCHISTOX publication[1] and parameterization documentation[2]
Aggregation for predisposition of individuals to uptake larvae	0.24	Parameterization documentation[2]
Proportion of cercariae that survive from one time point to the next	1/2	Graham et al's SCHISTOX publication[1] and parameterization documentation[2]
Proportion of miracidia that survive from one time point to the next	1/2	Graham et al's SCHISTOX publication[1] and parameterization documentation[2]
death prob by age	c(0.0656, 0.0093, 0.003, 0.0023, 0.0027, 0.0038, 0.0044, 0.0048, 0.0053, 0.0065, 0.0088, 0.0106, 0.0144, 0.021, 0.0333, 0.0529, 0.0851, 0.1366, 0.2183, 0.2998 , 0.3698, 1)	Parameterization documentation[2]

ages for death	c(1, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, 100, 110)	Parameterization documentation[2]
vaccine effectiveness	0.95	Graham et al's SCHISTOX publication[1] and parameterization documentation[2]
drug effectiveness	0.863 (*S. mansoni*); 0.94 (*S. haematobium*)	Parameterization documentation[2]
Specified age structure	c(8639, 9082, 6424, 5074, 4425, 3847, 3628, 3062, 2436, 1770, 1868, 1066, 743, 518, 355, 144)	Parameterization documentation[2]
Ages per index	5	Parameterization documentation[2]
Heavy burden threshold	400 eggs/1 gram faeces (*S. mansoni*); 50 eggs/10mL urine (*S. haematobium*)	Graham et al's SCHISTOX publication[1] and parameterization documentation[2]
Rate acquired immunity	0	Parameterization documentation[2]
Human larvae maturity time (in days)	30	Parameterization documentation[2]
Input ages	c(4, 9, 15, 100)	Parameterization documentation[2] and confirmed by workshop participants as the most appropriate for their purposes
Input contact rates	c(0.032, 0.610, 1, 0.06)	Parameterization documentation[2]
scenario	"high adult"	Parameterization documentation[2] and confirmed by workshop participants as adequate for the purposes of these specific simulation activities

Section 3. Participatory systems mapping results

Figure S1. Small group participatory systems maps: National level

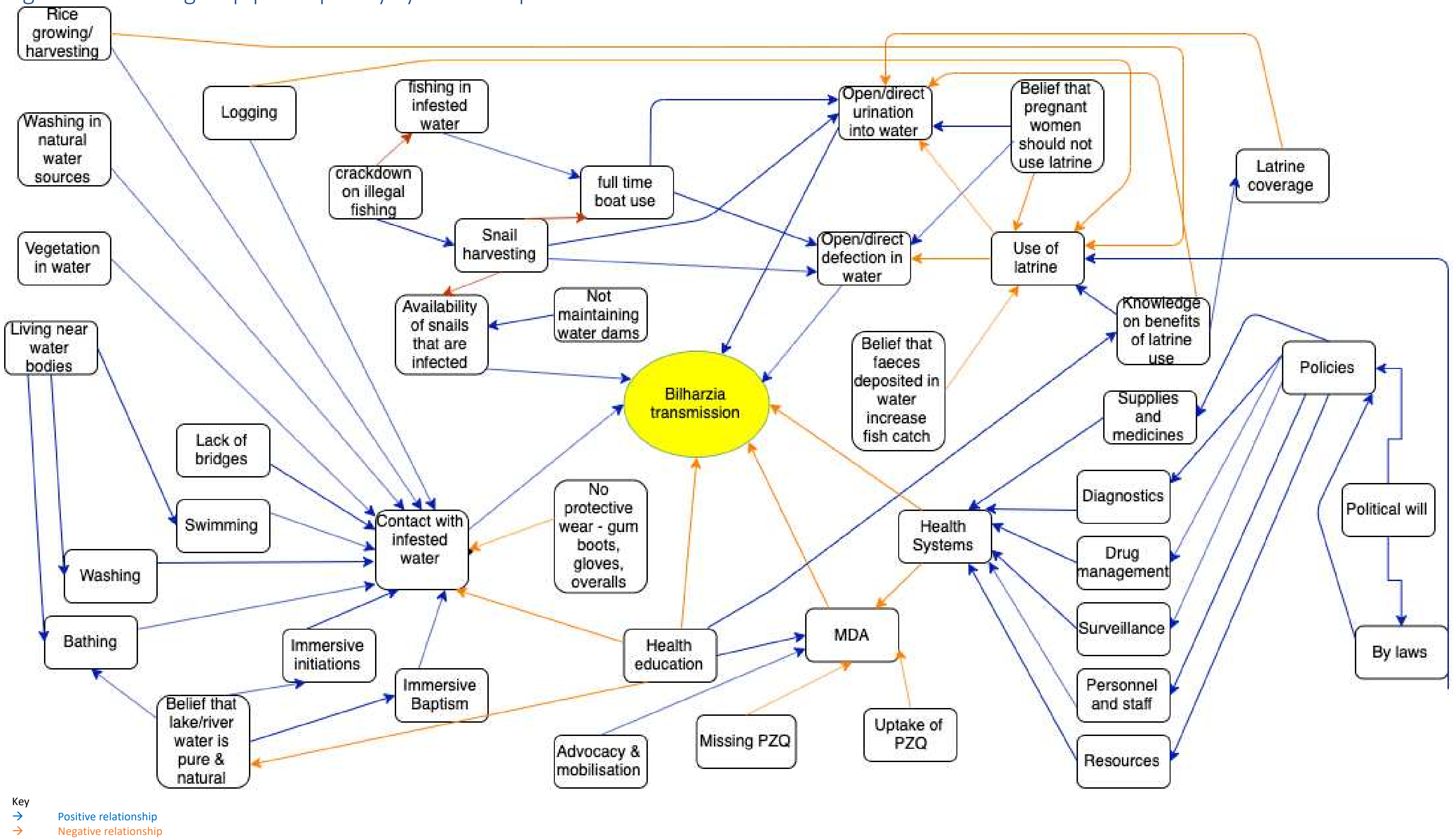
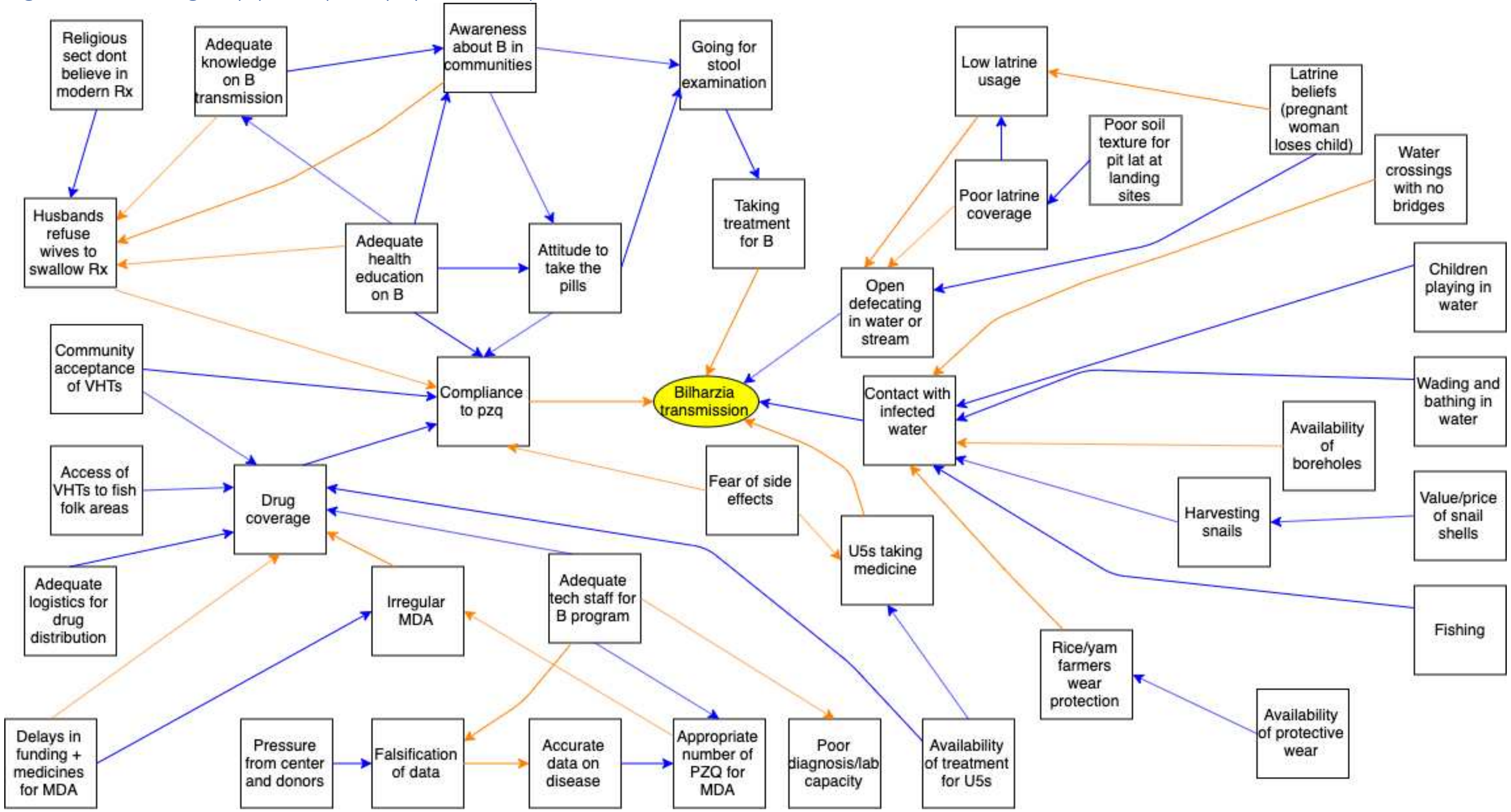
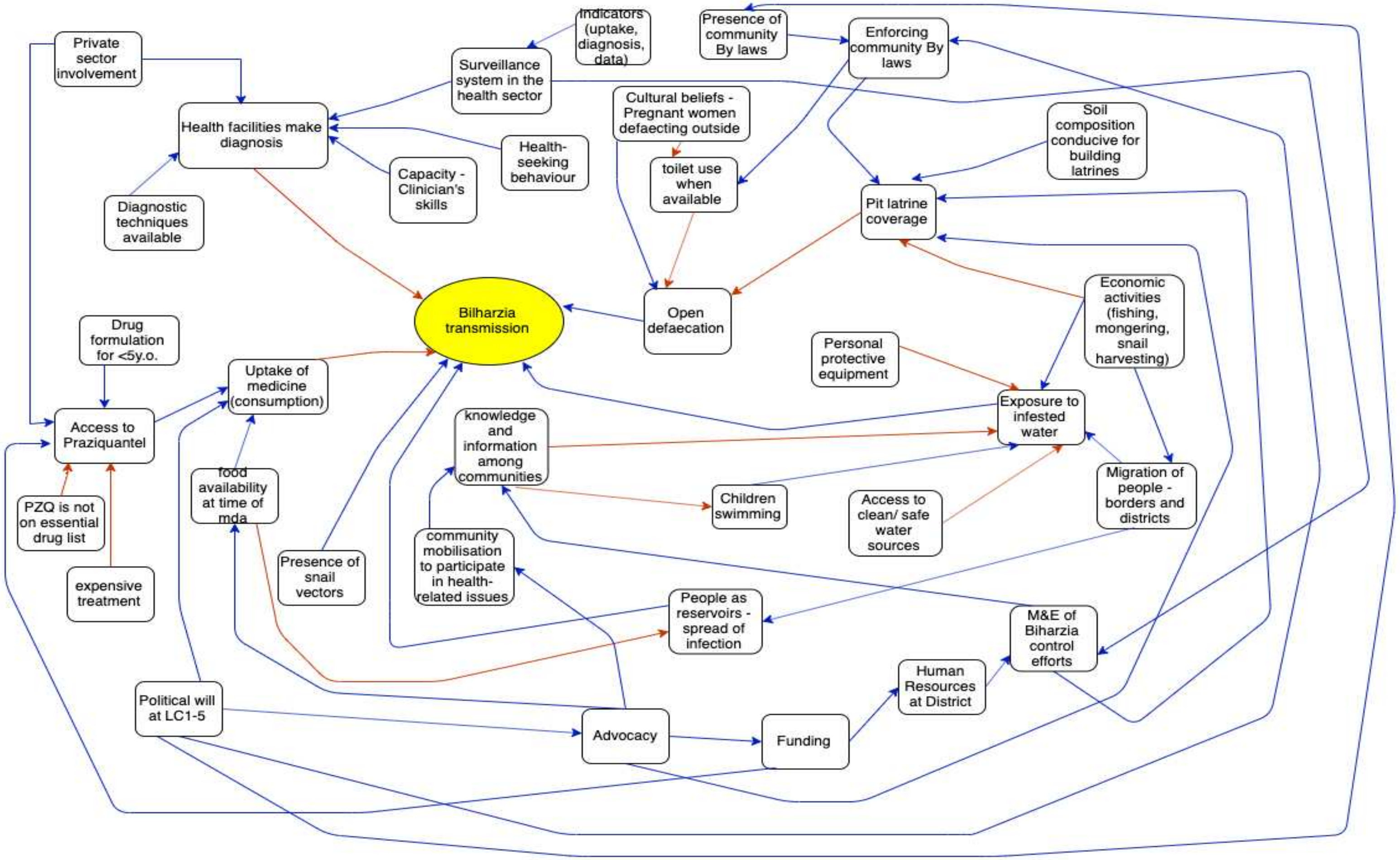


Figure S2. Small group participatory systems maps: District level 1



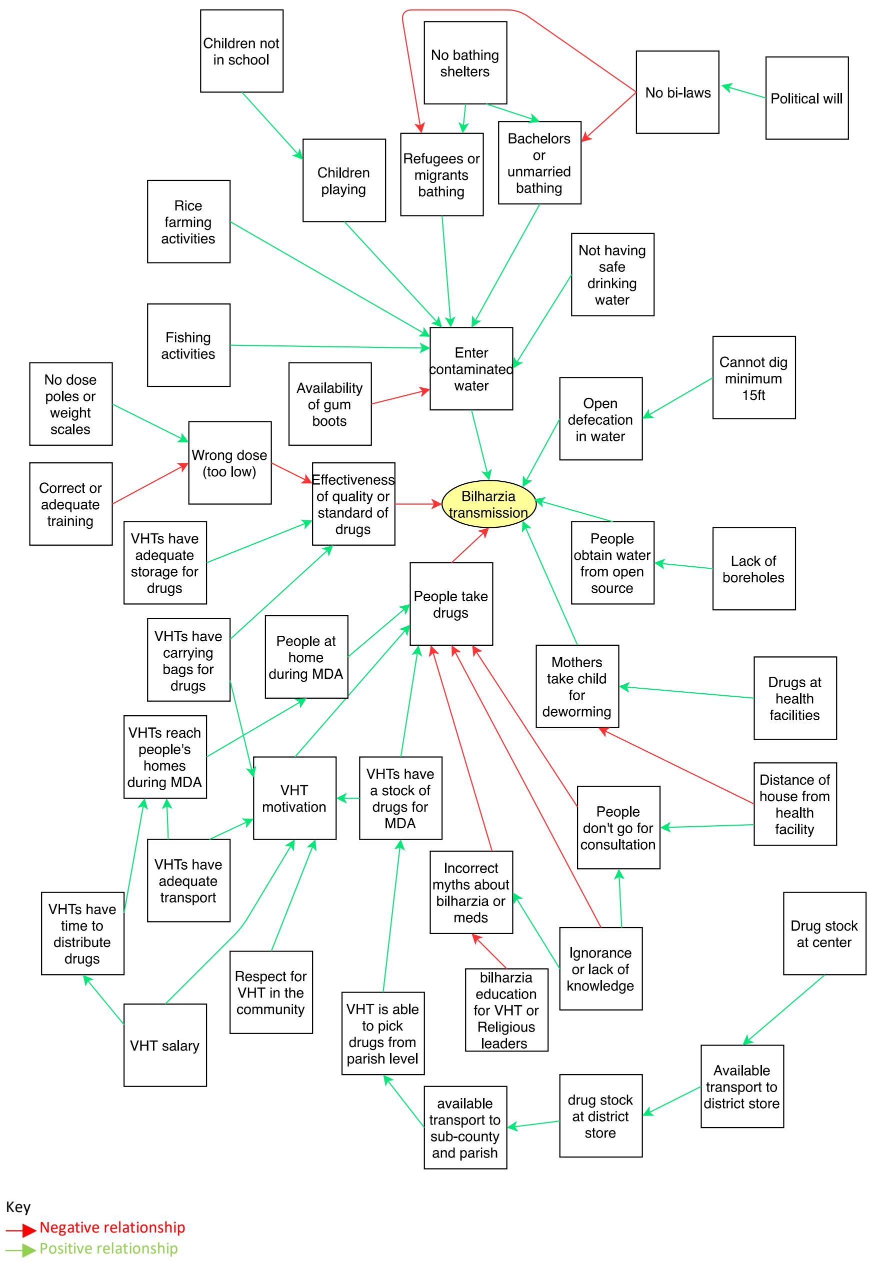
Key
→ Positive relationship
→ Negative relationship

Figure S3. Small group participatory systems maps: District level 2



Key
→ Positive relationship
→ Negative relationship

Figure S4. Small group participatory systems maps: Village level



Section 4. Excerpts of commentary from workshop participants on schistosomiasis transmission and control

Theme 1: Reasons schistosomiasis transmission continues after all these years of mass drug administration

- These people are fishing communities and so their fishing habits continue to be the same despite years of MDA. They continue to enter in the lake for fishing and other related activities, and therefore there's continuous infection and re-infection with schisto and other worms. This observation is in line with arguments that MDA alone isn't sufficient to control or eliminate schisto in endemic areas. As it is, MDA mainly focuses on treatment of people believed to be at risk of infection but does little to prevent people from being infected – at least for now, there's little or rather no evidence suggesting so.
- The behavioural change activities on schisto control is very low and seasonal, that's, it's only that time and period when there's MDA that the community gets to hear something related to schisto control. In other words, there's an uncoordinated behavioural change programs with regard to control of schisto. In so doing, key messages about how to break the lifecycle of schisto are often forgotten along the way.
- There's variation in sanitation standards in [district anonymised] and its surrounding areas. The soil textures in majority of landing sites in Uganda is sandy and so it's very difficult to dig and have long lasting pit latrines but even so, the fewer latrines dug are normally washed away during rainy seasons. So people resort to open defecation in the bush, around water streams and so on.
- Also, MDA coverage in the community is low. Most times, MDA program focuses on treatment of school going children with little attention to treating the whole community, and where the community is considered for treatment, the method of administering the drugs is not effective. The VHTs normally deploy two methods during MDA: first, is the door to door method where a VHT moves from household to household to administer drugs. This method has the following challenges. a) It is possible that a VHT may not find a single person in a household. In this case the VHT takes note of that HH for purpose of revisiting it. However, most times they (VHTs) don't revisit such HHs. b) After recording on drug register books, VHT administers drugs to HH members present and leave drugs for those missing. Here too, it comes difficult for VHTs to know whether or not the drugs would be delivered and swallowed. c) Due to fear of side effects, a family may decide not to take drugs at all. Second, is the administration of drugs in a central place. Here, VHT informs the community/village members about administration of drugs in a central place within the village. Also, considering distance and of nature of people's activities, fewer people may come for the drugs. In short, all these methods if not done with caution, have lots of unresolved issues about drug coverage, drug uptake and breaking the lifecycles of the disease.

Theme 2: Actions/Interventions to minimise contact with infested water

- There should be intensive and consistent education and behavioural change programs on schistomiasis control in the District/region. Physical engagement with fishing folks at landing sites and local FM radio stations should be consistently used to disseminate schisto control measures to the community. Also, posters clearly showing lifecycles of schisto should be erected in communities and messages translated in local languages like [language anonymised].

- There should be consistent and continuous sensitisation about hygiene and proper use of latrine, and where possible, the District, Sub-county, Parish and village leaders should all be involved in the dissemination of info and monitoring of compliance. Leaders mentioned therein can design Latrine Assessment Tools for purposes of showing both the coverage and use of latrines in the community. This way, HHs with sub-standard latrines can be identified and encouraged to improve, while those already cautioned but are not ready to improve after a period of time – per say 1 or 2 months can be summoned by the LC I court systems and punished for breaching minimum living standards.
- Encourage fishermen and rice growers to procure affordable water resistant gargets like gumboots so that even when they are fishing/cultivating, contact with infested water can be reduced.
- Lobby for safe water projects in the communities, like boreholes, spring water. Currently, [NGO anonymised] Field Office, is implementing a multibillion tape water project in [district anonymised] District. This project, if implemented well will help improve on the safe water coverage in the District and reduce the frequency mothers and children get into contact with infested water for domestic and other purposes.
- Install water treatment plants or equipments at landing sites so that infested water can be purified before being deemed safe for domestic use.
- Design specific programs, for example, registration and procurement of special gumboots for fishermen and rice growers so as to limit their level of exposure to schisto and other worms.
- Come up with projects that can help increase latrine coverage in the community. [NGO anonymised] for example has been constructing latrines/toilets in public places like schools, landing sites, health centres, and the organisation has been applauded for improving on sanitation and human waste disposal that would otherwise exacerbate transmission of schisto and other intestinal worms in the community.
- There should be continuous sensitisation and behavioural change activities so that the whole community gets equated with the lifecycle of schisto and how they can actively participate in eradicating it.
- Initiate and design a project that will enable fishing community diversify and engage in other welfare activities like poultry, piggery, bee keeping and so on.

Section 5. Network analysis results

Table S3. Network centrality metrics from full map

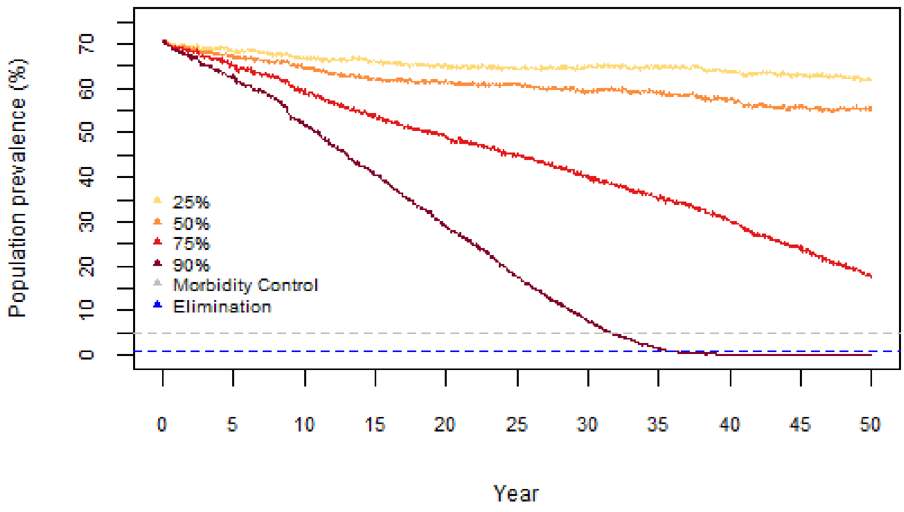
Factors	Indegree	Outdegree	Degree Centrality
Contact with infested H2O	25	4	29
Open defecation/urination	13	4	17
Schistosomiasis transmission	17	0	17
Adequate knowledge about SCH in communities	2	12	14
Latrine use	8	3	11
Proportion Fishing without protective gear	6	5	11
Snail harvesting without protective gear	4	7	11
Access to SCH drugs outside of MDA	6	4	10
Availability of latrines	3	6	9
Proportion of population ingest SCH drugs (PZQ)	8	1	9
Proportion of population ingest SCH drugs (PZQ)	8	1	9
Availability and use of protective gear for water work	1	7	8
People seek care for SCH	4	3	7
Playing and swimming	3	4	7
Access to potable water	2	4	6
Bathing in water bodies	3	3	6
Belief that pregnant women should not use latrines	0	6	6
Proportion of SCH cases with proper case management	4	2	6
Adequate diagnostic/lab capacity	3	2	5
Proper implementation of MDA	1	4	5
Proportion of Husbands refuse wives to swallow SCH drugs	4	1	5
Accuracy of SCH-related data reporting	2	2	4
Availability of drug formulation for U5s	2	2	4
Introduction and enforcement of local bi-laws	2	2	4
Political will/leadership related to SCH and WASH	0	4	4
Proportion rice farming without protective gear	1	3	4
SCH drug effectiveness/quality	3	1	4
Snail vector population	2	2	4
Water immersion rituals	2	2	4
Adequate health education in the communities	0	3	3
Adequate response to data	2	1	3
Advocacy about SCH at the district and national level	1	2	3
Community mobilisation for SCH activities	2	1	3
Funding for SCH activities	1	2	3
Households located near water bodies	0	3	3
Knowledge of benefits of latrine use	1	2	3
Lack specs for pit latrines	0	3	3

Migration to district for economic purposes	0	3	3
Mothers take children for deworming	2	1	3
Proportion logging without protective gear	1	2	3
Accuracy of M&E of SCH	1	1	2
Belief that faeces deposited in H2O increase fish stock	1	1	2
Enforcement of illegal fishing laws	0	2	2
Fear of side effects	1	1	2
Human resources for health at the district level	1	1	2
Infrastructure to avoid H2O, bridges	0	2	2
Prevalence of Myths about SCH and SCH meds	1	1	2
Price of SCH drugs	0	2	2
Washing in water bodies	1	1	2
Availability of bathing shelters	0	1	1
Food availability at time of SCH drug administration	0	1	1
Health worker mobilisation for SCH activities	0	1	1
Proper maintenance of H2O dams	0	1	1
School attendance	0	1	1

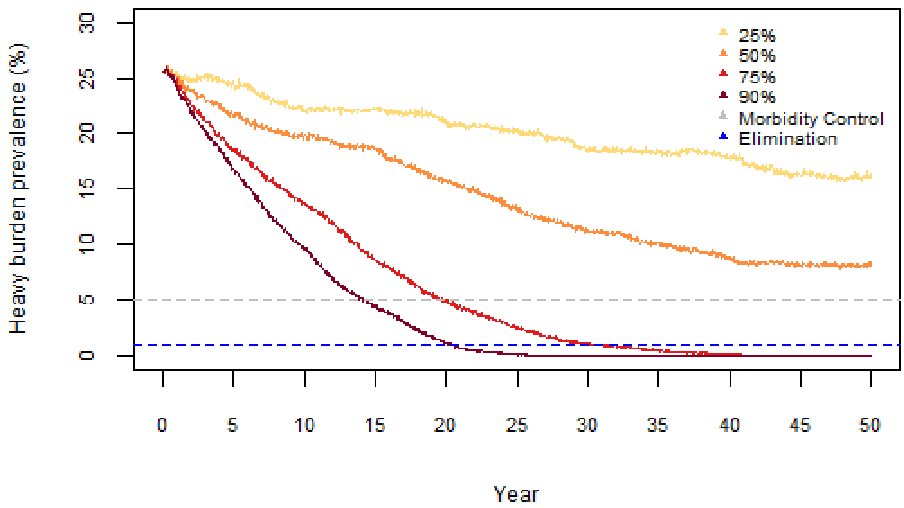
Section 6. Water contact simulation scenario results

Figure S5. Water contact simulation scenario – High prevalence *S. mansoni* settings

A. Population prevalence



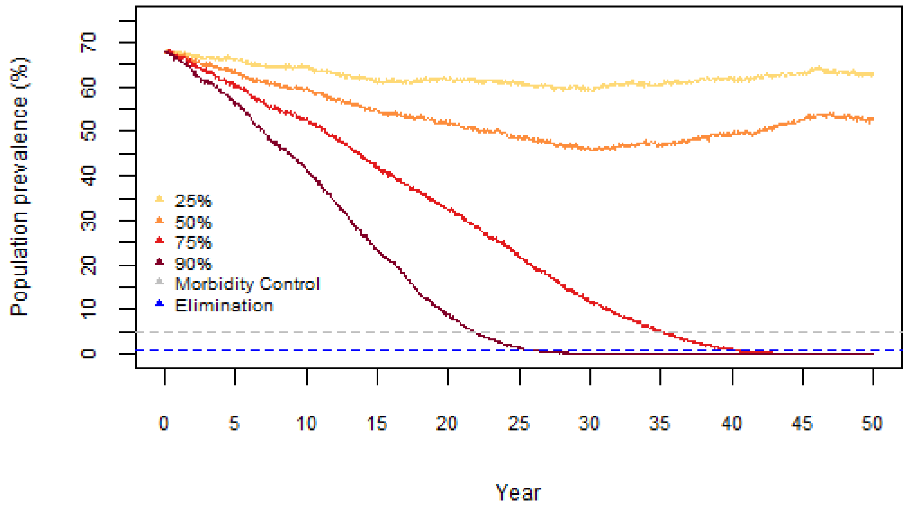
B. Heavy burden population prevalence



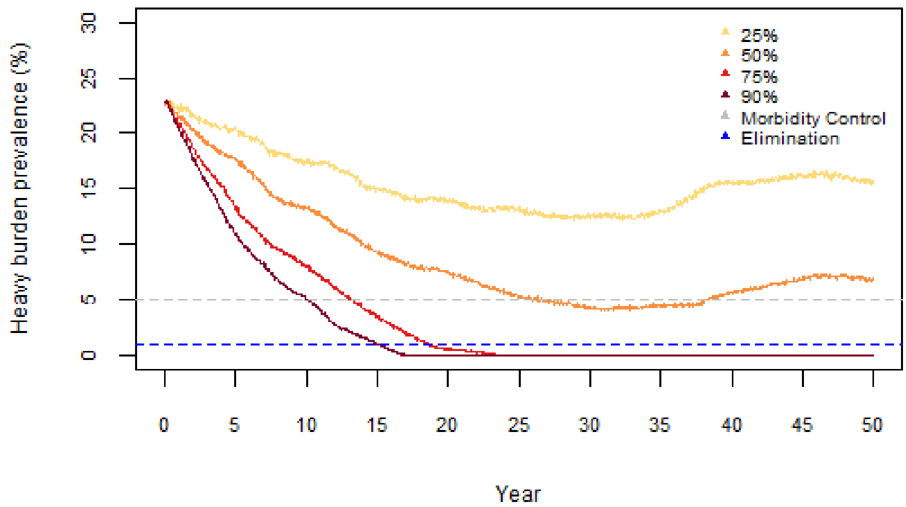
Note: Morbidity control, less than 5%; Elimination, as a public health problem, less than 1% prevalence ; 25%, 50%, 75%, 90%, reduction in infested water contact

Figure S6. Water contact simulation scenario – High prevalence *S. haematobium* settings

A. Population prevalence



B. Heavy burden population prevalence



Note: Morbidity control, less than 5%; Elimination, as a public health problem, less than 1% prevalence ; 25%, 50%, 75%, 90%, reduction in infested water contact