Journal of Humanitarian Engineering

Volume 7, Issue 1
ISSN 2200 4904

JOURNAL OF HUMANITARIAN ENGINEERING

Journal of Humanitarian Engineering (JHE)

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Cover photos: Examples of sustainable handwashing stations in Zambia by Warren Mukelebai Simangolwa

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GUEST EDITORIAL

Training engineers for local engineering excellence

The global engineering sector is in need of introspection. Engineers have always been recognised as being fundamental to the development and advancement of human society. Perspectives on how engineers should interact with and shape the development agenda are however changing. Young engineering leaders in particular are questioning technical zautocracy. Empathy is increasingly spoken of as a required attribute, alongside technical competency. Two paradigms have been instrumental in promoting a shift in traditional engineering training - humanitarian engineering and global engineering education principles. While humanitarian engineering focuses on meeting the needs of communities through the development of appropriate and sustainable technologies, global engineering principles focus on practicing as an engineer within a global and interdisciplinary context. The Engineers Without Borders (EWB) community has been a driver in defining and advancing both these paradigms.

Having graduated as an engineer in South Africa and accompanied many of my peers on their journey of developing technical competency, we are starting to see a third paradigm emerging as a fundamental aspect of engineering for the development and advancement of civil society - local engineering excellence. Since the 'Fees Must Fall' movement in South Africa, a series of student protests that swept South Africa's higher education sector in 2015 and 2016, students have initiated prominent debates to claim ownership of their learning journeys and shape knowledge production processes. Calls to 'decolonise engineering education' address the desire for technical education to be locally relevant and serve the lived experiences of economically marginalised South Africans, not only business districts in large metropolitan areas.

Humanitarian and global engineering practices are complementary to, but clearly distinct from, local engineering excellence. To realise pivotal progress towards the Sustainable Development Goals, it is vital to build local technical capacity beyond global corporations and international aid relief. For example, South Africa's water and sanitation sector is facing severe challenges of source contamination and overuse, which are amplified by drought and climate change. The Vaal River, one of the country's main water supply arteries, has been labelled a humanitarian crisis for several months. While humanitarian engineers may have the skills to address the crisis, and global engineers may have the perspective to develop long term interventions, it is the absence of competent, excellent and dedicated technical staff in the public sector that drives failures of public infrastructure due to insufficient record keeping, neglected maintenance and poor operating practices.

So how can local engineering excellence be promoted within engineering curricula? The Engineers Without Borders (EWB) international community has been a driver for transformation in the engineering sector across different geographies, and educational design challenges promoting humanitarian and global engineering principles have been pioneered in Australia and Canada, amongst other countries. At the end of 2018, EWB South Africa (EWB-SA) entered into a partnership with EWB-UK and EWB-USA to pilot an approach that converges humanitarian and global engineering principles with local engineering excellence. By locating EWB-UK's Engineering for People Design Challenge within a complex South African urban environment, we are exploring where synergies exist between delivering 'global' engineering curriculum content that has in the past produced primarily humanitarian engineering design solutions, to both international and local student audiences.

While still in the early stages of the project, we have observed that contextual sensitivity is critical when developing content for local student and academic audiences, as these are highly discerning about the power dynamics inherent in community representation. Careful selection of diverse local voices is thus key when local legitimacy must be retained. Similarly, it is important that communities are presented not only from a 'problem' perspective, but that agency, self-efficacy and the opportunity space that communities harness receive attention. Finally, we are observing that a purely educational approach with no roadmap for tangible delivery of results is viewed as insufficient by community partners, community members, academics and students alike. Local stakeholders view community insights as carrying intrinsic value, and a 'fair exchange' should reach beyond financial compensation for community partner organisations and into tangible improvements for community members more broadly. The dilemma is that community engagement at educational scale is intractable, while failure to engage deeply raises questions of knowledge extraction and threatens long term local legitimacy and sustainability.

It remains an exciting opportunity to explore curriculum transformation within a global EWB partnership. The shared organisational background allows us to build from a basis of good intentions and respect, which are critical foundational blocks when systemic power structures are brought under the microscope. Intentionally questioning the power dynamics inherent in humanitarian engineering and global development work remains an area of importance for EWB organisations as we collectively work towards building a more inclusive future for all people.

Wiebke Toussaint

Co-Founder, EWB South Africa; Executive Committee Member EWB International

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ISSN 2200 4904

CONTENTS

Community-Level Resource Development and Management Part 1: A Transferable Approach to the Analysis of Community Water Distribution System Expansion

Megan M. Richardson
School of Mechanical, Industrial and Manufacturing Engineering,
Humanitarian Engineering Program,
Oregon State University, Corvallis, OR, USA

Kendra V. Sharp* PhD
School of Mechanical, Industrial and Manufacturing Engineering,
Humanitarian Engineering Program,
Oregon State University, Corvallis, OR, USA
kendra.sharp@oregonstate.edu

* indicates corresponding author

ABSTRACT: *Access to water is extremely important in schools around the world, where students spend most of their day. As schools expand, particularly in areas with limited water resources, it is necessary to develop and manage water resources to ensure their sustainability. In this article, we describe a method of analysing water piping distribution networks using an open-source software package that allows practitioners to model the increased demands on water distribution systems associated with school growth. The methodology was then applied to the case study of a community-level water distribution system in rural Tanzania. Our intent is to provide a condensed description of a modelling method that can be used by field practitioners who may have limited technical background. Minimal tools are needed for practitioners to create their own system model, namely a global positioning system (GPS) device, tape measure, bucket, stopwatch and access to a computer with the downloaded software. Overall, the method and description herein is intended to be more accessible and straightforward to follow than others currently available to many practitioners, thus improving the ease of modelling for pre-planning and analysis of expansion or other water distribution system modifications.*

KEYWORDS: *Catchment system, Pipe network, Water, Water distribution, Tanzania*

1 INTRODUCTION

The Education is essential to social, economic and political development through access to opportunities and freedoms. Globally, education initiatives have promoted higher enrolment and learning for all, and such initiatives have been integrated into national policies. Across the 54 African countries, 44 have abolished school fees at the primary level (UNESCO, 2016) and six have already implemented free education at the secondary level (Masuda & Yamauchi, 2018). By eliminating part of the financial barrier to education, many countries have seen significant increases in enrolment. However, unless infrastructure and resources are also concurrently developed, schools can become overpopulated and under-resourced. Water security is one of many critical factors for keeping children in school because water is so essential for health, sanitation, food preparation and daily routines. Therefore, it is imperative to evaluate how school water supplies are meeting (or failing to meet) current system demands, how systems will need to be expanded to accommodate continued growth, and how management can ensure that systems are maintained reliably in schools. In this article, we use a freely available open-source software package

(EPANET) to evaluate the ability of an existing water catchment system to meet the water supply needs for a potential school expansion and the associated growth in student population. The program allows the user to consider fluctuating demand at taps in a water system throughout the day, calculate maximum output at each tap based on system architecture and known source, evaluate how demand changes with increased student enrolment, and determine the feasibility of potential design strategies for integrating supplemental water capacity into school infrastructure.

We describe a transferable method that has general application to the analysis of potential expansions of community-scale water systems. As a case study and detailed example, we apply the method to the analysis of the water catchment and potential expansion of the delivery system at Matema Beach High School (MBHS), a government secondary and advanced-level school in south-western Tanzania. Of the school's 1,000 students, boarding students (males aged 18 to 25) in the advanced-level program live on campus full-time, whilst day students (males and females aged 13 to 18) in the ordinary level program spend the majority of their weekdays on campus, from 6:30 A.M. to 5:00 P.M. The school is preparing for increased enrolment at the advanced-level with the addition of science programming.

We project estimates of the increase in the school's water demand with increased student enrolment. We then use EPANET to model and analyse the existing water catchment, piping infrastructure, and impact of increased enrolment on resource availability. We create a model of an expanded system based on the additional infrastructure and piping network that would be built to accommodate additional students. Lastly, we include local water storage options in our model to evaluate possible options for integrating additional storage capacity (e.g. tanks) into the infrastructure on campus to serve more students. As in many other rural water systems, there are some uncertainties in the details of the infrastructure (e.g. pipe configuration, underground fittings and pipe bends) and even the overall supply. Thus, we have made the best assumptions we can and have been conservative in our estimates of quantities that would limit flows (for example, we overestimated expected pipe lengths and losses in new latrines).

The authors selected EPANET due to Richardson's experience with the software and the setting of the case study. Working in a rural village, Richardson, like many volunteers, had limited access to educational and methodological resources including system analysis tools related to water development projects (Peace Corps, 2018). The information gap she experienced motivated our work to document a straightforward modelling strategy and applied case study so that others could replicate the approach when working in similar settings to analyse their own water systems, particularly to assess the capacity for expansion. Thus, we have distilled disparate manuals, examples, and other resources down to a concise description of methodology with case study application intended to be easily accessible to development workers or volunteers working in the field, including those both with and without significant technical backgrounds. We further selected an open-access publication outlet with the intent that our work can be beneficial to those outside of academia or those working rurally who have limited or no access to databases, libraries, and library subscriptions to publications. Resource development in schools is particularly relevant as it often aligns with both national and international initiatives. For example, Tanzania's National Strategic Plan in schools relates the development of safe water provisions to better support of student performance, attendance and health (Ministry of Education and Vocational Training, 2012), and the United Nations' (UN) Sustainable Development Goals include ensuring availability and sustainable management of water and sanitation for all (Zhu, 2015).

2 FIELD RESEARCH METHODS

Matema Beach High School receives its water supply from a catchment built in the mid-2000s. While "catchment" is often defined differently in water resources science, our use of the term in this article is in accordance with local Tanzanian terminology. In this terminology, catchment describes the constructed pool of water retained by a hollow trapezoidal wall that creates a version of a settling tank.

Water flows into the piping system through the top grate of the trapezoidal wall and through piping down to the community. The water collected in this catchment comes from a river flowing down the Livingstone Mountains. To evaluate the capacity of the catchment and water piping system connected to the school, Richardson used a Garmin GPSMAP 64ST (Garmin Ltd., 2016) to collect location and elevation data between the catchment and school, summarised in Table 1. The GPS unit was also used to

Table 1: *Distance and elevation change between the water catchment and the campus*

Elevation head (m)	Total pipe length (m)
82	1,025

Figure 1: *Catchment structure with water overflow during the end of the rainy season* (*dog and person included for scale*)

measure the distances between each of the taps on campus and the junction where the piping entered the campus from the catchment.

To determine the catchment's functionality throughout both the rainy and dry seasons, the site was observed monthly. During all visits, the catchment was filled to capacity and overflow was observed across the retaining structure, suggesting that there is consistent excess water supply under the current conditions (shown in Figure 1). The assumption of excessive water supply requires iterative re-evaluation as the school's water supply system is incrementally expanded.

Three pipes are connected to the base of the hollow trapezoidal wall as intakes that serve solely to supply the school with water. The largest of the three intake pipes is made of steel and was measured to have a 9 cm (3.5 inch) inner diameter.

Throughout the school day (from 6:30 A.M to 5:00 P.M), Richardson observed water use from the taps across campus, and also asked boarding students when they collected water from the taps. It was noted that the highest number of students were using the taps between 6:30 to 7:30 A.M, when performing chores prior to their first class. The chores included mopping floors and cleaning bathrooms. Advanced-level students also reported washing each morning. At the time of the field study, up to 48 taps could be operated simultaneously (located in the bathrooms, showers, and at outdoor all-purpose taps).

To determine the current flow rate from each tap, the amount of time required to fill a 20 L bucket was measured and recorded at three different taps on campus. When the taps were opened completely, which is how students use the taps, the average time to completely fill the bucket was 155 seconds. The flow rate from each tap (Q_{tap}) is solved using Equation 1; through conversations with users, we found this flow rate to be acceptable in meeting the operational needs of the community.

$$Q_{tap} = \frac{20\,[L]}{155\,[s]} = 0.13\,[L/s] = 0.00013\,\left[m^3/s\right] \qquad (1)$$

3 DEFINING THE SYSTEM

Matema Beach High School is serviced by a piping network that distributes water to taps across campus to meet standard daily water demand for applications in bathrooms, kitchens, gardening, laundry, and cleaning of school facilities. In our network model, we divided the 48 taps operating at peak demand into seven clusters across campus. These clusters are assumed to be connected to the primary junction of the piping from the catchment. The details of the various possible branching topologies are unknown; therefore, some simplifying assumptions must be made. We recommend re-running and re-evaluating the model output after, say, addition of an additional tap grouping and before adding other tap groupings to evaluate the accuracy of the model and modify assumptions if needed.

All of the clusters are located on a campus map in Figure 2. The incoming flow from the main pipe is split between the clusters, so this incoming flow rate (Q_{in}) is equal to the sum of flow rates to the seven clusters.

$$Q_{in} = \sum_{n=1}^{7} Q_n \qquad (2)$$

The measured distances between each of the tap clusters and the primary junction is listed in Table 2, along with the number of taps assigned to each cluster. An additional 10 metres of piping is added in the model for each bathroom building to account for plumbing connections; this is a conservative estimate accounting for additional minor losses caused by additional bends and fittings. The term "minor losses" refers to pressure losses due to fixtures and components such as bends and tees. "Major losses" refer to pressure loses attributed to friction at the

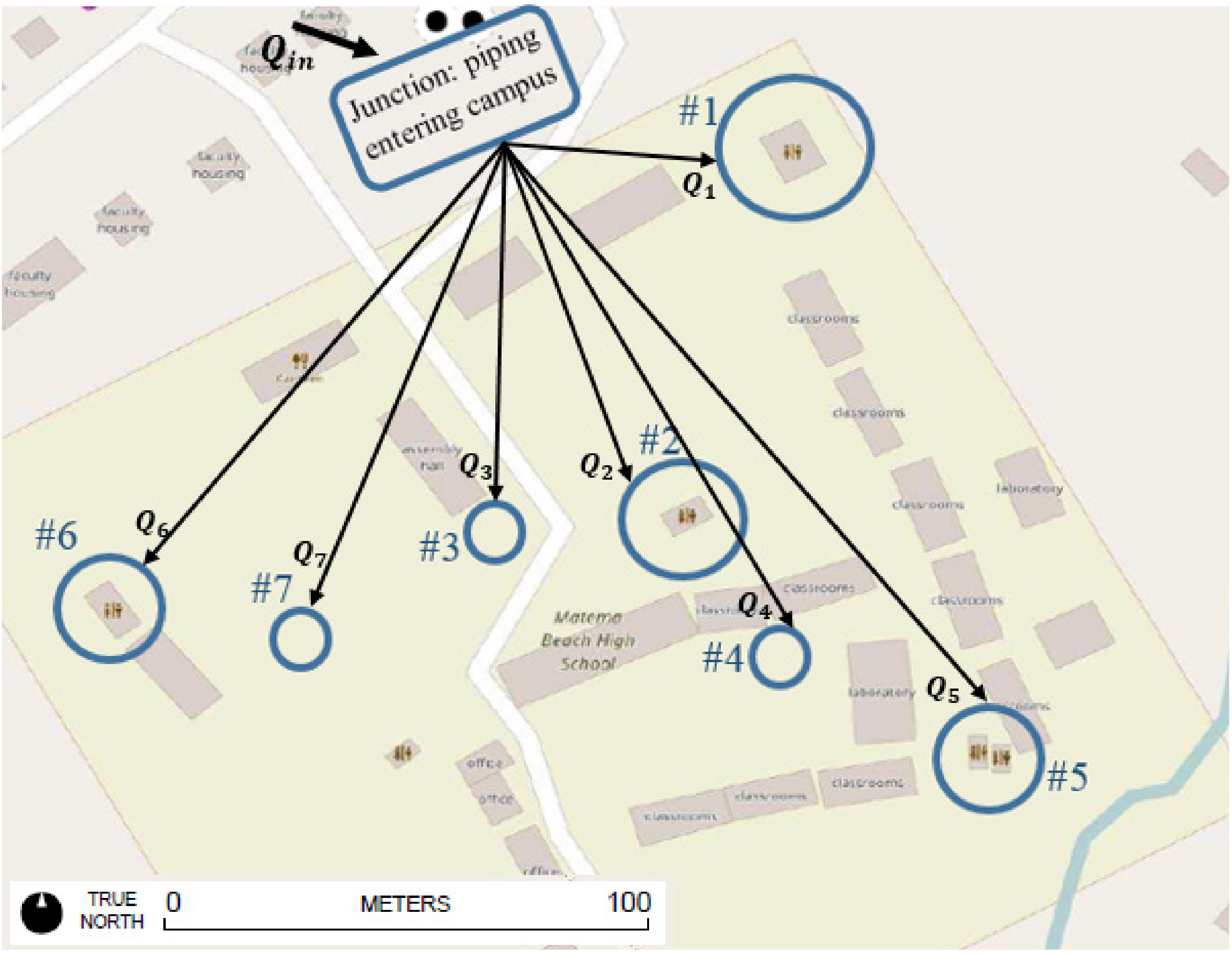

Figure 2 (top): Locations and distances between the seven clusters of taps. Q_{in} *is the flow rate into the school system.* Q_1 *to* Q_7 *represent the flow rates at clusters 1 to 7 respectively*

pipe walls. We limited our analysis to water supply; the water is not currently treated and treatment is outside the community motivated scope of the work.

4 SYSTEM MODELLING WITH EPANET

To evaluate the extent to which network expansion is possible, we modelled both the existing and expanded tap networks using EPANET (https://www.epa.gov/water-research/epanet), an open-source software from the United States Environmental Protection Agency that can be used to model drinking water distribution systems (Murray, 2008). This program and accompanying User Manual can be downloaded in English via the link above, or in several other languages from other sources, as noted in the references section.

In EPANET, users can create a model of a network of pipes, nodes (or pipe junctions), pumps, valves, storage tanks and reservoirs, and run their model to calculate the flow of water in each pipe and the pressure at each junction based on given inputs (Rossman, 2000).

It was useful to input the typical local component properties (e.g. material, roughness, and inner diameter for pipes, type of valve, etc.) as the "default" settings for the project at the outset so these properties were automatically populated for each component added when building the system model. If a property, such as length, was different than the default for a specific component, that property was manually changed for the specific component. As we found some of the entries or entry boxes non-intuitive, screenshots showing the properties entered into the EPANET model can be found in Figure A1 to A5 of Appendix A.

Quantities such as roughness were estimated based on recommended values in the manual (Rossman, 2000) for standard polyvinyl chloride (PVC) pipe since that is the most commonly used material in the MBHS area. Valve type (pressure-reducing valve, PRV) in the model was also

Table 2: Tap cluster details: locations, number of taps/cluster, and distances to a central junction

Cluster no.	Location	No. of taps	Distance to primary junction (m)
1	north bathrooms and communal tap	17	70
2	central bathrooms	6	150
3	communal tap by main hall	1	160
4	communal tap by classrooms	1	200
5	east bathrooms	6	250
6	south bathrooms	16	210
	south bathrooms		

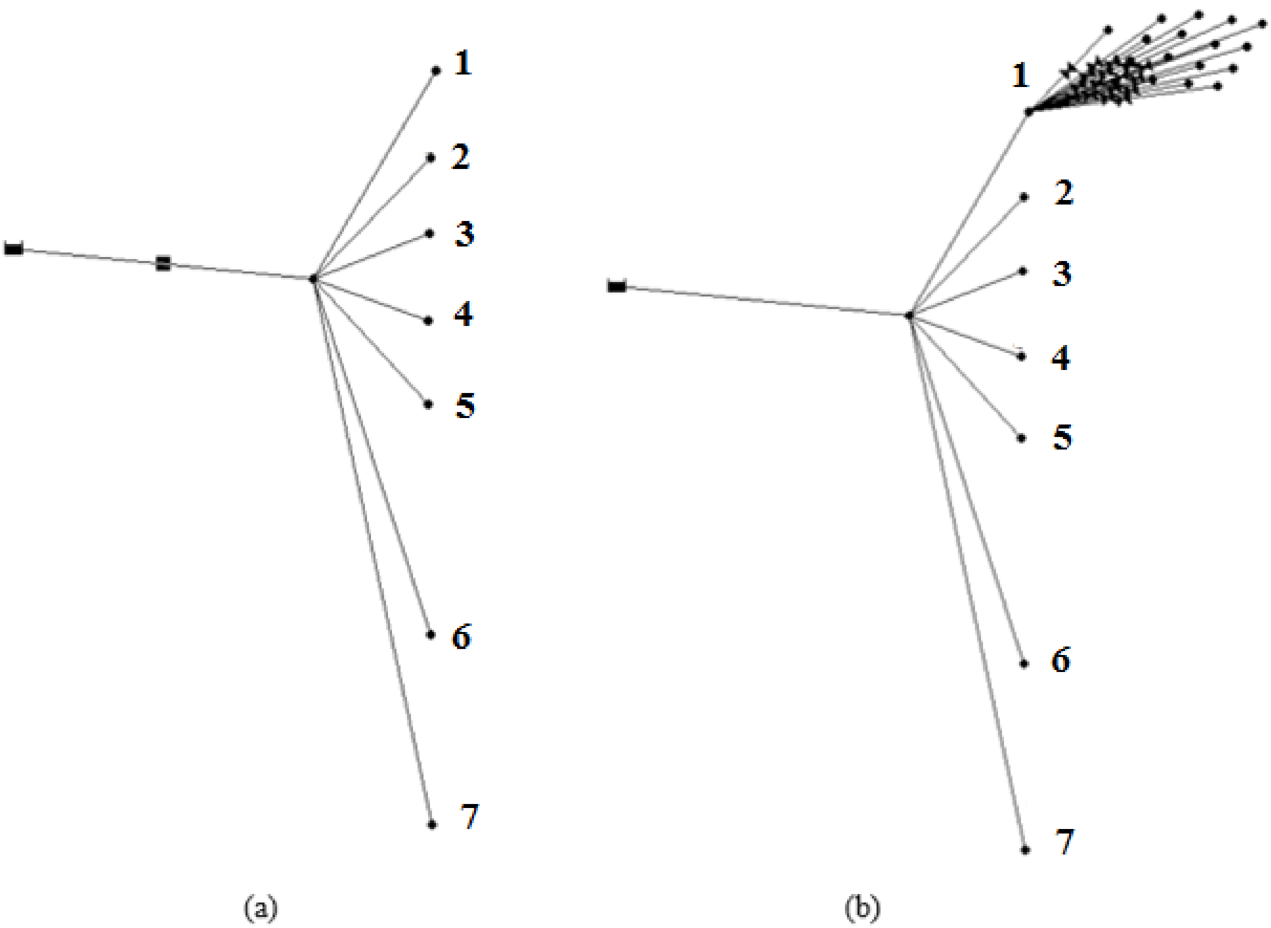

Figure 3: (a) The seven clusters are added to the model, and (b) each of the 17 junctions and valves are connected to Junction 1. Note: the distances between the clusters and valves in the figure are not to scale.

selected based on typical components. The Hazen-William formula was selected as an appropriate head loss formula (Murray, 2008). We found it easiest to work in imperial system units as the software provides a clear indication of specific units expected for each parameter and variable in comparison to the use of the metric system. We used US gallons per minute (gpm) for our flow rate units.

The first step in building a system model in EPANET is to select a water storage element, in our case, a reservoir to represent the water catchment, and connect the storage to a junction with a pipe. The necessary inputs include total head (elevation) for the reservoir, elevation at each junction, and length, diameter, and roughness for each pipe (see Figure A1 to A1 of Appendix A). We note that height, elevation and length should be input in feet whilst the diameter is input in terms of inches in this specific software. The reservoir was assigned a total head equal to the elevation difference between the catchment and the school's campus, whilst the elevation of the primary junction (where the pipe entered school grounds) was set to zero based on the assumption that the main junction is installed at the most easily accessible elevation, namely the campus elevation. Pipe length was estimated from the measured global positioning system (GPS) data and inner pipe diameter was measured in the field.

Next, we were able to begin modelling the tap distribution by locating the first cluster with a junction and connecting it to the primary junction with a pipe. The pipe properties were consistent with those of the reservoir pipe, but the length was taken from Table 2. Seventeen taps are located in cluster one, which were drawn into the model as 17 junctions each with a valve connecting the tap-junction to Junction 1 (illustrated in Figure 3(b)). Junction and valve properties were set according to base demand, valve diameter, loss coefficients and valve type (see Appendix A Figure A2). Base demand is the flow rate required out of each tap. For our model the rate was set at 0.13 L/s (2 gpm), the observed flow rate from each tap in the current physical system. Tap diameter was 0.025 m (1 inch) and the loss coefficient, related to pipe and valve components, was a sum of the individual coefficients for changes in pipe diameter, pipe bends associated with the tap, and properties of the specific type of valve (Munson et al., 2013). Our model incorporated two 90° threaded bends, a sharp-edged change in diameter, and assumed that the globe valve was fully opened. Pressure-reducing valves (PRVs) were modelled as fully open, which is how they are operated at the school. If needed, the model can be modified so that demand can be estimated for non-reducing valves.

The process of adding junctions and valves was continued until the entire current pipe network was represented in the model with each of the seven junctions connected to its own cluster of taps. The valve diameter, loss coefficient, valve type, base demand and status were assumed constant across the network, representing peak demand and simultaneous tap use. The current-system model ran successfully showing that demand at each tap was met. Should the model not run successfully, this indicates that the currently configured system model, including desired flow rates, is not theoretically solvable and that there is either insufficient supply or head for the desired flow rate, or that there is another problem in the system.

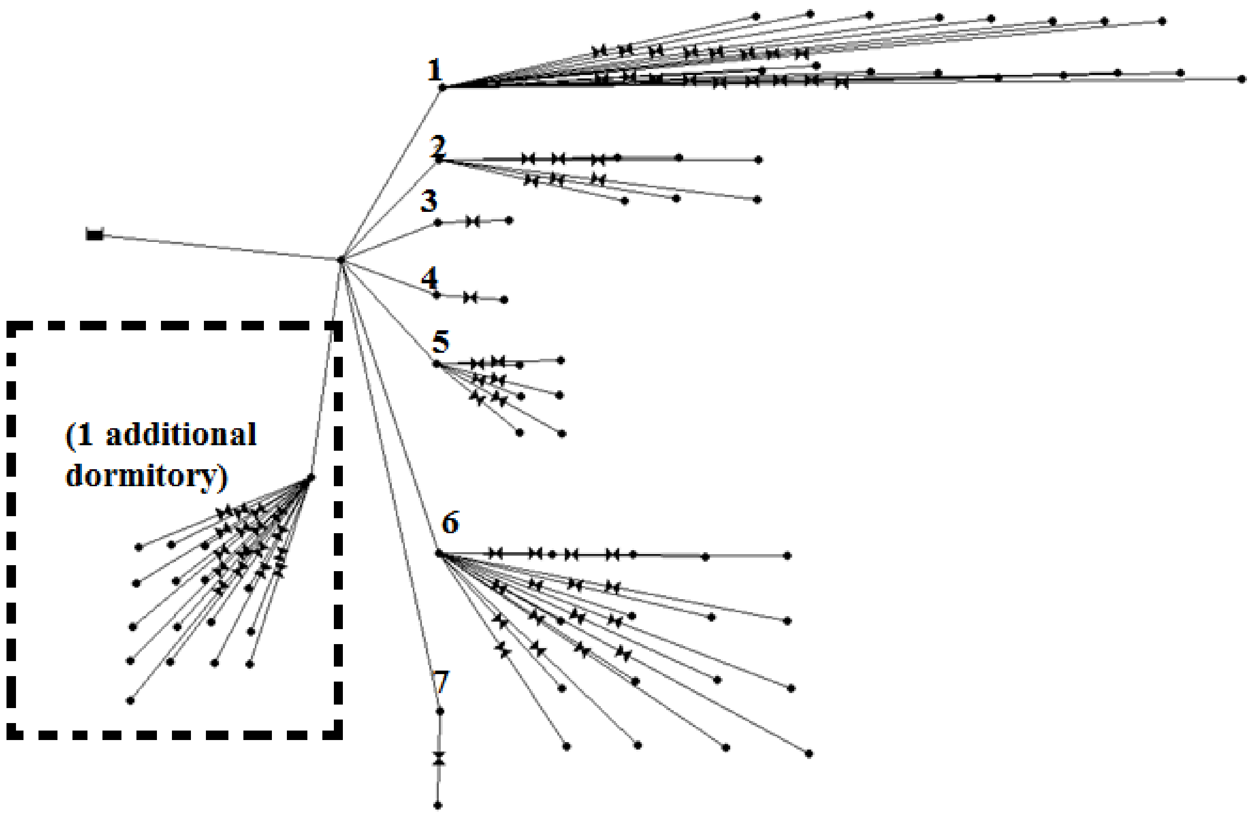

Figure 4: *Existing water distribution network at MBHS, with one additional dormitory constructed*

5 CONCLUSIONS & RECOMMENDATIONS

5.1 Expanding the pipe network system

Our model showed that with the current base demand (0.13 L/s) from taps across campus, there is still substantial head available from the reservoir to expand the piping network. This capacity for expansion is important because the school is planning to expand its advanced-level program of boarding students to include a science curriculum. The increase in enrolment will require expanding the school's infrastructure, including classrooms, laboratories, dormitories and bathrooms. Each dormitory and accompanying bathroom constructed for students will increase the total number of taps and therefore the school's overall water demand.

The current on-campus student dormitories each accommodate approximately 50 male students, so we assumed 50 students per additional dormitory. Each new dormitory will require a common tap to be installed outside of the structure for general use, and eight toilet stalls and eight showers in a bathroom. In total this means that for each addition of 50 advanced-level students, 17 new taps will need to be connected to the piping network that will operate during peak demand. In EPANET, each additional dormitory was modelled with an additional tap-cluster connected to the primary junction. The properties of junctions, pipes and valves that we used can be referenced in Figure A3 Appendix A with the exception of pipe length, which was estimated to be the average distance to existing clusters. The school's expansion plan tentatively locates new dormitories closer to the main junction; however, we conservatively assume an average pipe length between the primary junction and new tap-cluster equal to the distance to the current dormitories.

Our model runs successfully with the addition of one dormitory and its associated water demand, suggesting that that the school can increase enrolment by 50 students and demand by 2.6 L/s with the existing supply and connection to the water catchment. To determine the maximum number of additional dormitories and the total demand that the current catchment can supply, we continued to add tap-clusters until the network was no longer able to compute the analysis, at which point it was indicating that the desired demand (input flow rate) cannot be met. This process of adding tap-clusters showed that the reservoir could accommodate up to five additional dormitories in its piping network. Therefore, we estimate that MBHS could enrol up to 250 new advanced-level boarding students before needing to provide additional water storage infrastructure.

5.2 Expanding with additional water storage capacity

In order to expand beyond 250 students, or to build more than five dormitories connected to the pipe network, it would be necessary to construct additional water storage. One approach to ensuring water availability for the additional dormitories and bathrooms is to integrate water storage capacity (in the form of an elevated tank) into the dormitory design. The tank would need to be filled daily during non-peak demand (for instance, in the evening or at night) and would be used to provide a dormitory's worth of students with their needed volume of water at the same flow rate provided as the rest of the taps on campus.

The daily water needs of an individual boarding student were estimated based on both observations of and conversations with the advanced-level students. In addition to individual needs, water is required for daily dormitory and classroom cleaning. Given a population of 50 students, we assumed that this group would represent two classes of 25 students each and then estimated water demands for the entire group, given in Table 3.

Table 3: Individual, group, and overall daily water needs for 50 boarding students

Individual Water Demand (L)		**Group Water Demand (L)**		**Overall Water Demand (L)**	
Bathing	10	Mopping the dormitory	40	(Total individual water demand) = (Number of students) × (Individual Demand)	1,000
Drinking	3				
Dishwashing	2				
Bathroom	3	Mopping two (2) classrooms	40	(Total Group Water Demand)	80
Hand washing	2				
Total	**20**	**Total**	**80**	**TOTAL**	1,080

Each dormitory of students would require approximately 1.08 m^3 of water to meet their daily needs. Locally, tanks are available in volume increments of 1 m^3. To ensure that adequate supply would be available and to include a factor of safety in the case that the tank was not always filled completely by the start of each day, we selected a 2 m^3 tank per dormitory for our model.

A new cluster of 17 taps was drawn into the EPANET model. However, this cluster was connected to a water tank rather than the reservoir. The same demand and properties at the junctions and valves were inputted but the pipe properties were altered. The most accessible pipes from nearby hardware suppliers are PVC pipes with a 2 inch (50.8 mm) internal diameter. This scale and type of pipe was modelled and pipe length was estimated to be 30 m (accounting for the distances from the tank to the bathroom and outdoor tap, and plumbing within the bathroom). The dimensions of a 2 m^3 water tank were also included for the tank properties of diameter and initial level (where the height of the tank equalled its initial level when full) (Izoplas, 2018). Initially we modelled the tank as set on the ground with base elevation of zero to determine if just the initial height of water in the tank would provide adequate pressure to supply the base demand.

The network (visualised and with parameters listed in the appendices) ran successfully, indicating that the initial water level was high enough to provide adequate total head to meet the local demand. However, the water level will drop throughout the day as the tank drains. To ensure that there would be sufficient head in the elevated tank system to provide a consistent flow rate throughout the day to the taps supplied by the water in the elevated tank, we continued to iterate in our model runs for this isolated system. We iteratively ran the model, each time decreasing the initial water level in the elevated tank until we reached a minimum head at which the system would compute (meaning that the tap demand could be met). Our calculations suggest that a minimum head of 1.5 meters is required (to top of water surface) to meet the tap cluster demand from a tank source. We note that the energy losses due to the >1,000 m of piping from the catchment source and the many associated piping components (e.g. valves, bends, etc.) are much greater than those in this supplemental elevated tank or nearby tap cluster system, explaining why a much smaller amount of head is needed to achieve the desired flow rate in the supplemental tank cluster system. Adding in a factor of safety and recognising that the base of the elevated tank needs to be at the minimum elevation to meet tap cluster supply, we suggest elevating the tank to two meters. The prescribed structure height to support this tank was consistent with that of other water tanks in the district, so we concluded that constructing a platform connected to the wall of the dormitory two meters tall would be feasible.

Finally, to ensure that the tank would be used effectively each day, we proposed and analysed a filling schedule that could be integrated into the existing student chore routine; a manual filling process is consistent with filling methods used at other similar schools with elevated tanks and piped water although an automated process could be installed if resources are available to do so. Time-to-fill could be calculated assuming that the flow rate into the tank equalled the flow rate from each of the taps.

$$Volume = Q \times time \tag{3}$$

$$2\,m^3 = 0.000129\,\left[m^3/s\right]* \times \, time\,[s]$$

$$time = 15,500\,[s] = 4.3\,[hrs]$$

The tank would require just less than four and a half hours to fill completely. This procedure could be started daily before dinner (at 6:00 PM) and then would be completed before enforced lights out for the dormitories (at 11:00 PM). With each dormitory's existing chore-management student structure, the procedure could be easily integrated into daily routines.

6 DISCUSSION

The current piping network of MBHS's water distribution system was modelled using EPANET's open source software to determine the extent of expansion that the built water catchment could support. Given the existing measured flow rate from taps, the catchment can accommodate up to five additional dormitories of demand (or 250 students) by supplying adequate pressure to 85 additional taps. Assuming that the catchment is still providing sufficient water supply on a year-round basis, further expansion would be possible by integrating additional water storage into the dormitory infrastructure. Given that a dormitory sleeps 50 students, the model showed that an additional 2 m^3 water tank could be raised two (2) meters above the ground to provide adequate pressure to all the taps associated with a dormitory.

Although our system was modelled with a reservoir, this does not mean an infinite supply of water is available to the community. The source supplying the catchment is a river running down the Livingstone Mountains. If the village government were to expand the distribution system by attaching more outlet pipes to the catchment, there would come a time when the water being drawn from the system would approach the river's supply into the catchment. At this point, the flow rate to each tap would decrease. For future work, we suggest that the catchment supply be quantified over a one to two-year cycle, and that any impact on catchment supply be closely monitored with incremental expansions of the school. Our system model could be iteratively improved by improving the fidelity of the assumptions based on field measurements of supply and flow rates at the taps during stages of the expansion.

In addition, a major difference between the model and reality is that when we expand our system to the point at which the reservoir cannot supply the demand we dictated as needed in the model, the model states that the system is not solvable. In reality, at that point, the system would not stop functioning, but rather the flow rate from each tap would decrease.

Throughout this article we were able to meet each of the goals of the study related to estimating expansion capabilities and supplementary storage options. We were able to successfully use the open source software to model the current water distribution system and determine the extent of expansion that this system could accommodate. Beyond network expansion, we were also able to design local water storage that could accommodate additional increases in student enrolment. In future work, this methodology could be compared to other distribution system development and analysis approaches to determine its relevance in the larger scope system modelling and low-resource environments.

7 CONCLUSION

In this article we demonstrated a pipe network analysis method to evaluate the expansion of a community-level water distribution system. This type of methodology is particularly relevant for community development practitioners and volunteers working in highly rural settings. Our application of the method proceeds through the steps of system modelling to analyse expansion capacity and supplementary storage design. The method's major advantage is that it can be employed in a low-resource environment as it only requires basic tools, including: a GPS, tape measure, bucket, stopwatch and computer with EPANET software installed. Our approach and documentation are designed to be simple to follow and accessible to those without a technical background or who have not previously worked on community water system projects, rather than a method developed for professional engineers designing city water distribution systems. Our goal is to further disseminate this written resource to those working in the field that could utilise a simplified water-system-analysis methodology, and to have practitioners with non-technical backgrounds test the usability of this methodology. One group we are aiming to reach is Peace Corps Volunteers, as they are continually working directly with communities. We are especially interested in seeing this written resource used by the volunteers and communities together to develop and manage local water systems.

8 ACKNOWLEDGEMENTS

This research was possible due to the support of Matema Beach High School's students, teachers and staff. The Peace Corps staff and volunteer community in Tanzania provided language, technical and cultural training as well as continual support throughout my service; special thanks to program managers Paul Mairi and Anna Isanzu. This study was made possible by of Oregon State University's School of Mechanical, Industrial and Manufacturing Engineering's collaboration Peace Corps Master's International program, which enabled and supported Richardson's non-traditional degree track.

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10 APPENDIX A

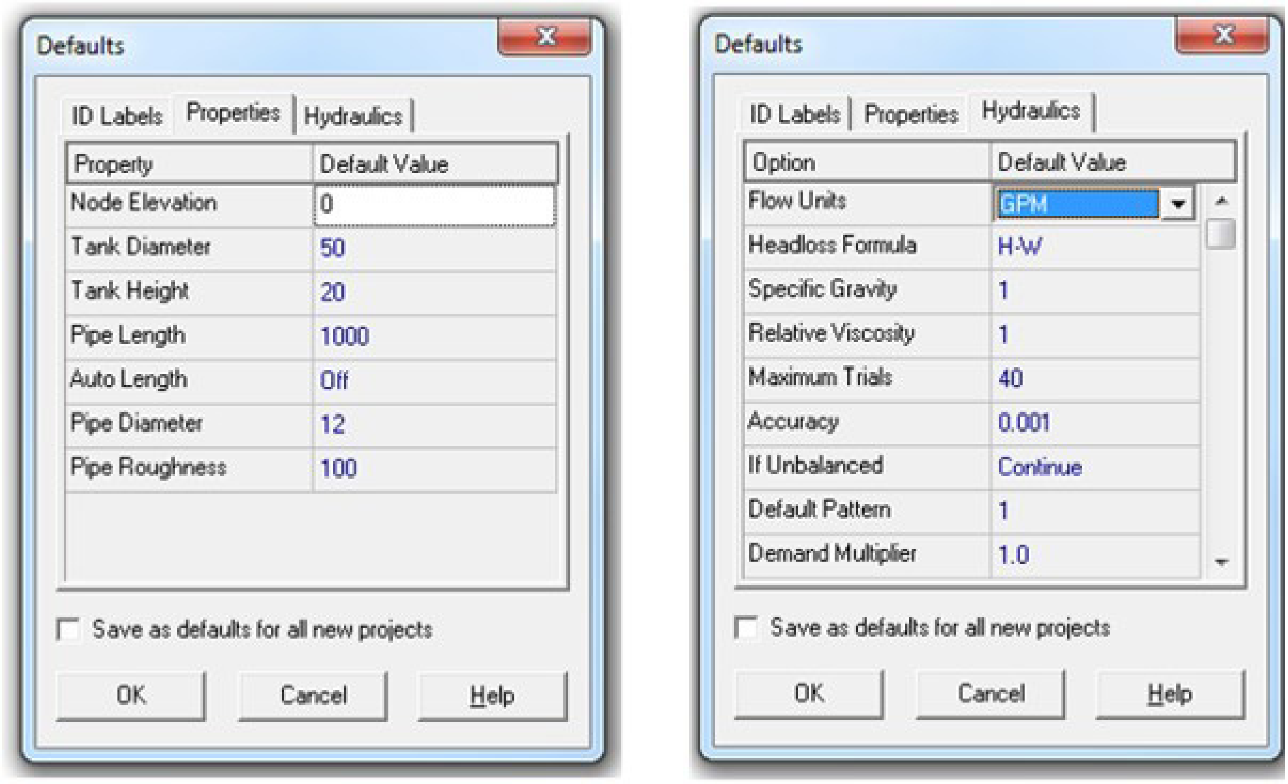

Figure A1: Default properties and hydraulics when setting up an EPANET model

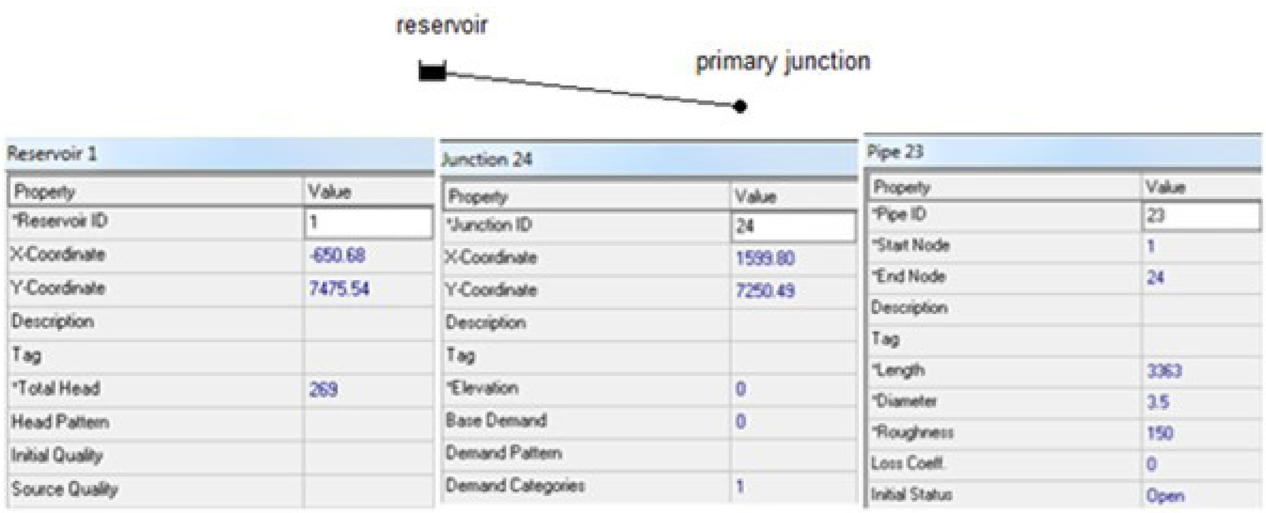

Figure A2: Reservoir-to-junction model and component properties

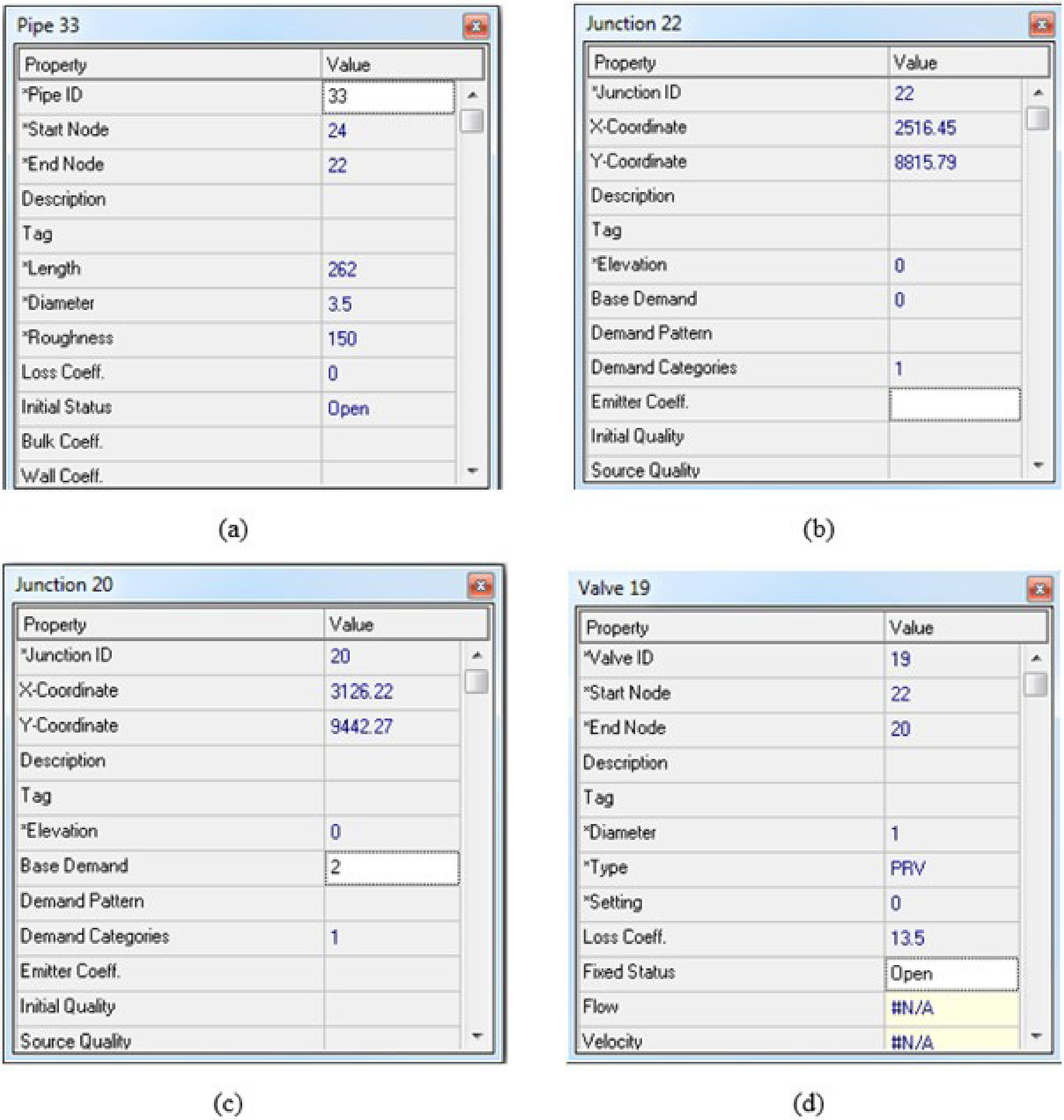

Figure A3: *Properties set for (a) the pipe connecting the primary junction with junction-1, (b) junction-1, (c) each of the 17 junctions in the tap cluster, (d) each of the 17 valves*

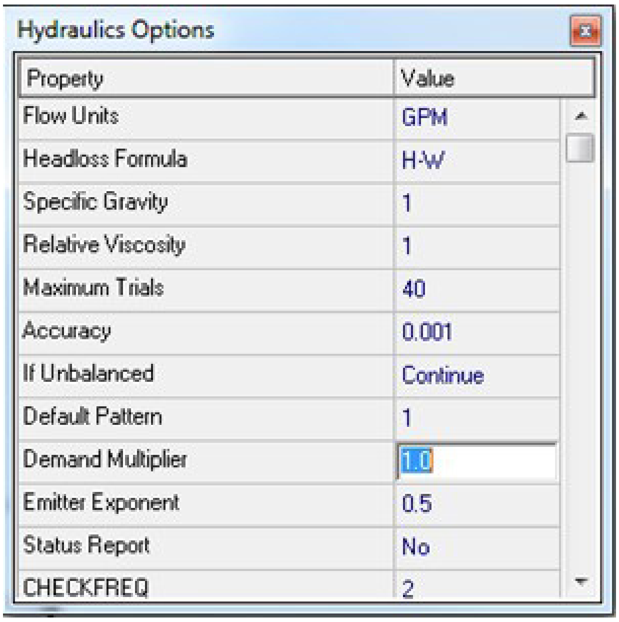

Figure A4: The location of the demand multiplier within analysis options

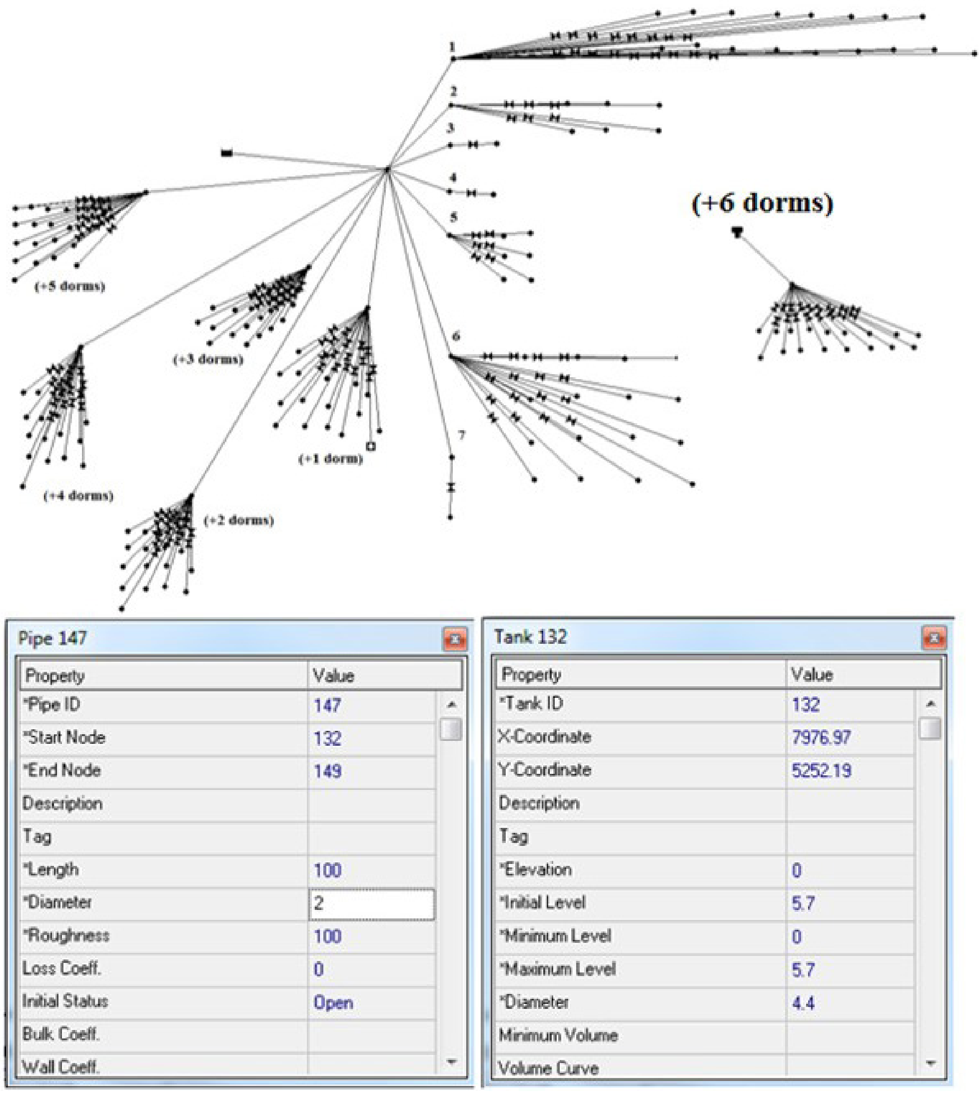

Figure A5: The expanded system with an additional 6th dormitory, and the pipe and tank properties for the local water capacity

Community-Level Resource Development and Management, Part 2: A Transferable Approach to Feasibility Analysis for Biogas as an Alternative Cooking Fuel

Megan M. Richardson
School of Mechanical, Industrial and Manufacturing Engineering,
Humanitarian Engineering Program,
Oregon State University, Corvallis, OR, USA

Kendra V. Sharp* PhD
School of Mechanical, Industrial and Manufacturing Engineering,
Humanitarian Engineering Program,
Oregon State University, Corvallis, OR, USA
kendra.sharp@oregonstate.edu

*corresponding author

ABSTRACT: *Energy access for all is the seventh Sustainable Development Goal (SDG) put forth by the United Nations in 2015. This sustainable development goal has been taken on by many non-governmental organisations (NGOs), national governments and communities alike. Traditional Sub-Saharan African approaches to cooking often rely on three-stone fires (or other open wood fires). The smoke from these open cooking fires is known to cause significant adverse health impacts. Thus, access to cleaner energy sources is especially important to improve cooking conditions. One alternative cooking fuel is biogas, which has the advantages of smoke reduction, and decreased reliance on and impact of firewood collection. In this article, we develop a method of analysing the feasibility of biogas projects for some rural communities. The method we describe enables both evaluation of small-scale anaerobic digester designs for specific settings and determination of the scale, cost, and effectiveness of a biogas digester. For example, in a cooking application, 1 m³ of biogas can replace 1.3 kg of firewood and the associated time (approximately 10 minutes) spent collecting firewood. Such technology evaluation is critical for helping communities and organisations determine whether this type of project is well suited for their settings. All too often, development project concepts are funded prematurely, before the realisation that the implemented technology does not function properly or is unsustainable for specific applications. The feasibility analysis we describe is a contribution to the literature, because it provides a condense and, simply written resource to enable development practitioners, volunteers and communities in a rural setting, evaluate sustainable biogas energy solutions prior to investment and implementation.*

KEYWORDS: *Alternative fuel, biogas, cooking fuel, digester, energy, Tanzania*

1 INTRODUCTION

Without access to alternative fuels, students in rural areas around the world spend time away from the classroom collecting firewood to contribute to meal preparation. Dependence on firewood in schools impacts the time students spend on study and contributes to deforestation (Global Alliance for Clean Cookstoves, 2016).

Alternative fuels such as biogas can potentially reduce the issues associated with firewood collection and use in rural settings. Biogas is defined as the mixture of gases (predominantly methane and carbon dioxide) that is generated from the degradation of organic material in oxygen-free or anaerobic environments. Biogas can be generated and stored in specialised vessels known as anaerobic digesters or biogas digesters.

We developed a methodology for development practioners to evaluate the feasibility of biogas as an alternative fuel source to firewood. The methodology allows practitioners to determine biogas digester type, sizing and resulting biogas yields. The methodology also allows for an assessment of the impact of biogas digester sizing on fuel costs. Our intent is for development practitioners to utilise our approach to determine if this type of energy generation technology development is appropriate for their application and setting.

This paper presents feasibility assessment methodology and its application to a case study for sizing and costing of a community-scale biogas digester. We investigate the feasibility of using human waste to power the plant, with regards to both sanitary and social constraints, and detail the process of plant sizing for a specific population of users and beneficiaries. Matema Beach High School (MBHS), a government school of approximately 1,000 students in southwestern Tanzania, is utilised as a case study for this methodology. The analysis aims to determine if biogas is an effective alternative cooking fuel compared to firewood fuel. The analysis focuses on: biogas digester type selection, basic cost of construction, and evaluating the biogas yields of the chosen design, along with local acceptability.

We developed this analysis method by collating information from other resources and distilling key points into a condensed and accessible format that can be used by practitioners. Our primary goal is to aid development practitioners and volunteers in evaluating the feasibility of biogas infrastructure in rural settings. Currently, volunteers have many educational resources related to community development, but lack thorough technical resources related to energy development (Peace Corps, 2018). Determining the cost and effectiveness of energy systems prior to construction and implementation can inform sustainable system design including the use of local resources and appropriate long-term planning of system maintenance. As this method requires minimal technical background to use, it is ideal for practitioners outside of academia who do not have access to databases and libraries whilst working rurally. The development of simple-to-use evaluation and planning methods for schools is particularly important as it aligns with national and global initiatives. The Tanzanian government has promoted renewable energy development through policy and funding, particularly in rural areas (Mshandete and Parawira, 2009). Likewise the United Nations (UN) organisation has pushed for reduced reliance on non-renewable fuels by promoting access to affordable, reliable, sustainable and modern energy for all in its Sustainable Development Goals (Zhu, 2015).

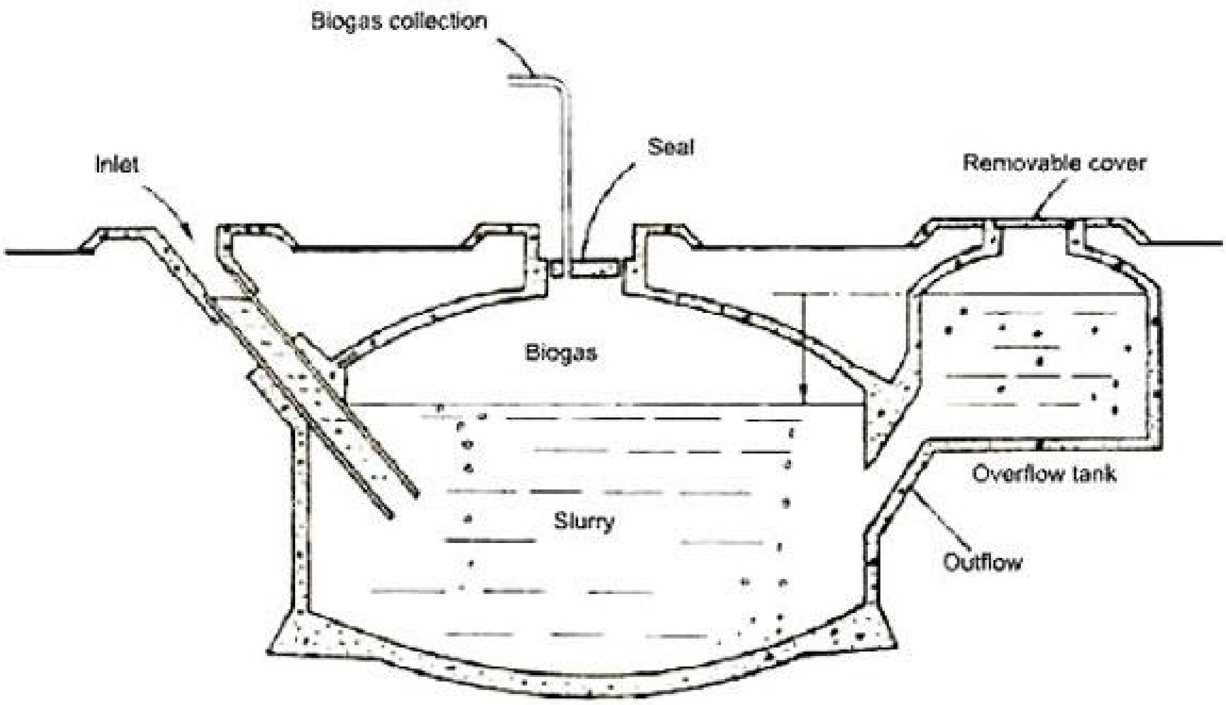

Figure 1: *Simple fixed-dome biogas digester* (*Li, and Ho,* 2006)

2 BIOGAS TECHNOLOGY REVIEW

We begin a feasibility analysis by determining which type of biogas digester would operate most effectively in the school's environment.

As described above, biogas can be generated from the fermentation or digestion of organic materials by specialised bacteria that exist in oxygen-free (anaerobic) environments. Organic wastes include: human and animal excreta, food waste, garden waste or other liquid organic wastes (e.g. fats and oils).

Biogas digesters are specialised vessels that enable the generation, capture and storage of generated biogas. Biogas digesters are designed for two specific functions – digestion or fermentation of the input waste in an oxygen-free "digestion" chamber, and collection of the generated flammable gas in the gas holder or gas storage chamber. A general biogas digester design is shown in Figure 1 to illustrate those two functions.

The six most common biogas digester designs commonly seen in rural development settings are reviewed here based on their construction, operation, and maintenance.

2.1 Fixed Dome

A fixed dome biogas digester (Figure 1) is a conical brick and mortar wall construction with fixed concrete shell roofing that acts as an immovable biogas holder.

The fixed dome plant is constructed using locally available materials: brick and mortar, concrete for shell-roofing, PVC piping, and is partially buried under a layer of soil (Kuria and Maringa, 2008). The cost of materials is low with the greatest costs attributed to the use of highly skilled masonry labour and the use of heavy machinery. The gas-tightness of the fixed dome chamber is dependent on the skill of masonry available; average

Figure 2: Applications of the six most common biogas digesters: (a) fixed dome[1]; (b) floating drum[2]; (c) earth-pit[3]; (d) ferro-cement cage[4]; (e) balloon[5]; and (f) composite material[5].

Notes:

[1] *https://commons.wikimedia.org/wiki/Commons:Reusing_content_outside_Wikimedia,*

[2] *https://energypedia.info/wiki/File:Floating_drum_mauretania.jpg,*

[3] *https://kendallpermaculture.com/2013/07/05/biogas-project-update-may/,*

[4] *https://www.sciencedirect.com/science/article/pii/S1364032114001968 and*

[5] *http://www.build-a-biogas-plant.com/balloon-digester/*

masonry does not create a gas-tight dome and additional sealants or plastic liners must be used to prevent leakages. The use of additional sealants and liners creates a risk to safety due to the possibility of dome explosion due to gas pressure build-up if no suitable depressurisation, venting and flaring of excess gas is allowed for (Kuria and Maringa, 2008).

The fixed dome digested is continuous-feed digester that can vary in size with volumes ranging between 6 to 20 m^3. Typical operational lifespans are between 12 to 20 years with a specific biogas production rate of 0.2 to 0.5 m^3 of biogas per m^3 digester volume $m_{gas}{}^3/m_{volume}{}^3$. The specific biogas production rate can be interpreted as a kind of efficiency; the gas production efficiency compared to the digester volume would be 20–50%. However, gas produced is not visibly indicated to the user and fluctuates in pressure. Fixed-dome plants are recommended only if they will be utilised by experienced biogas technicians who are familiar operating the technology (Werner, Stöhr and Hees, 1989).

Minimal regular maintenance is required as no metal or moving parts are involved in the design; instead, daily additions of influent generates the mixing requirement to break-up scum and enhance gas production (Werner, Stöhr and Hees, 1989). However, if repairs are needed, the only access to the digester is through the influent and effluent chambers. Therefore repairs are difficult to perform, and cracking could lead to irreparable leaks and structural damage (Cheng et al., 2014).

The overall strength of the brick and mortar structure is high. In terms of reliability, the amount of gas produced relates directly to the mass of the waste provided; gas produced will not be released at a constant pressure, which could negatively impact the cooking application.

2.2 Floating drum

The floating drum digester is an underground cylindrical or dome-shaped construction containing an internal moving gas holder (Figure 3).

The digester is typically constructed as a brick-lined pit supporting a cylindrical steel floating drum. The drum can either float directly above the fermenting waste slurry or in a water jacket. The biogas generated is collected in the gas drum that rises and falls in accordance with the volume of gas generated.

The floating drum design has a comparatively high initial cost due to the steel and machining needed for its construction, however the overall construction is simple and can be performed by local masons and metal workers (Cheng et al., 2014). The reduction in cost for the use of average masonry skill in comparison to the skilled masonry required for fixed dome digesters is balanced by the cost of skilled metal labour.

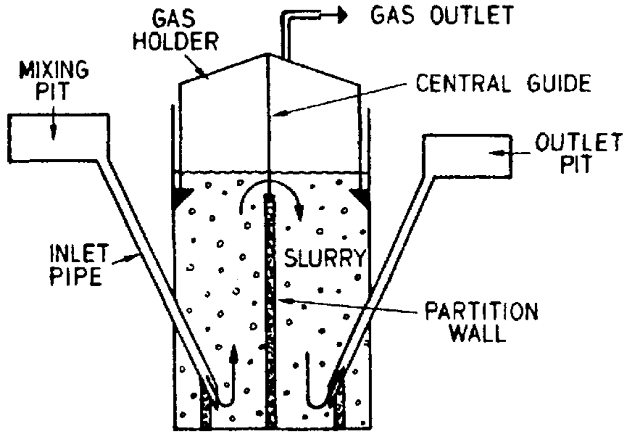

Figure 3: Cross-section of simple schematic of floating drum biogas digester (Marchaim, 1992)

The drum is rotated to encourage enhanced biogas production. Inside the drum, a steel bar framework disturbs and breaks apart the scum layer formed at the top of the accumulated waste as the drum is rotated (Kuria and Maringa, 2008). As the drum can move vertically with changes in gas levels, the plant produces biogas at constant pressure, which is advantageous for cooking (Werner, Stöhr and Hees, 1989). The drum height is an easily interpretable visual indicator of gas storage levels to the user.

The digester is sized from 6 to 100 m^3 with an expected specific daily biogas production rate of 0.3 to 0.6 $m_{gas}{}^3m/m_{volume}{}^3$. This can be interpreted as 30 to 60% gas production efficiency. The digester lifespan ranges from 8 to 12 years, this is lower than the fixed dome due to the effects of corrosion on the drum (Werner, Stöhr and Hees, 1989). Chemical additives could potentially mitigate the effects of corrosion without significant impact on the digestive process; however, investigating such possibilities was beyond the scope of this study.

During maintenance and cleaning, the metal drum can be removed for ease of access into the digester. Regular maintenance requirements include drum painting (for optimal sealing), rust removal, and dislodging the drum if it gets stuck in floating scum and cannot rise. The metal structure provides high strength and reliability (Kuria and Maringa, 2008). This type of digester is recommended when reliability is of greater importance than cost. The interior painting helps to ensure that the digester is gas-tight, and its movement with gas production prevents the possibility of a plant explosion. Within a local environment that experiences heavy and cyclic rainfall, it is possible for rain to seep into the pit, with the maintenance frequency increasing with rust build up (Polprasert, Nukulchai and Rajput, 1982).

2.3 Earth-pit digester

The earth-pit plant digester (Figure 4) is a design that is suitable for stable soils where masonry walled digester designs are not required. The earth-pit plant is typically an earthen pit lined with a thin layer of cement, with or without steel mesh reinforcement, to prevent seepage of the digester contents to the surrounding soil (Werner, Stöhr and Hees, 1989). The edge of the pit is reinforced with a ring of masonry that serves as the anchorage point for the gas holder. The gasholder construction material can vary, is it typically either a metal construction or plastic sheeting. Where plastic sheeting is used, the sheeting is attached to a wooden frame that extends down into the fermenting slurry and anchored in place to counteract buoyancy (Werner, Stöhr and Hees, 1989).

The earth-pit is a continuous feed digester that is typically sized between 4 to 500 m^3, with a daily production rate of 0.1 to 0.5 $m_{gas}{}^{3}m/m_{volume}{}^{3}$, or a 10 to 50% gas production efficiency.

The earth-pit plant design requires minimal construction materials: cement for pit lining, metal netting and plaster walls to prevent seepage, and a masonry ring. In addition, an external gasholder (metal or plastic) is recommended. The cost of installation is the lowest of the technologies described in this paper (approximately one fifth of the cost of a floating drum plant) however this is in turn balanced by a short operational lifespan of 2 to 5 years. The overall structural integrity of the digester is low as it lacks structural supports. Despite the design being suitable in stable soil conditions, it must be situated above the groundwater table to avoid groundwater contamination and dilution of the waste slurry. Maintenance of the plant is minimal, typically consisting of occasional plaster repairs.

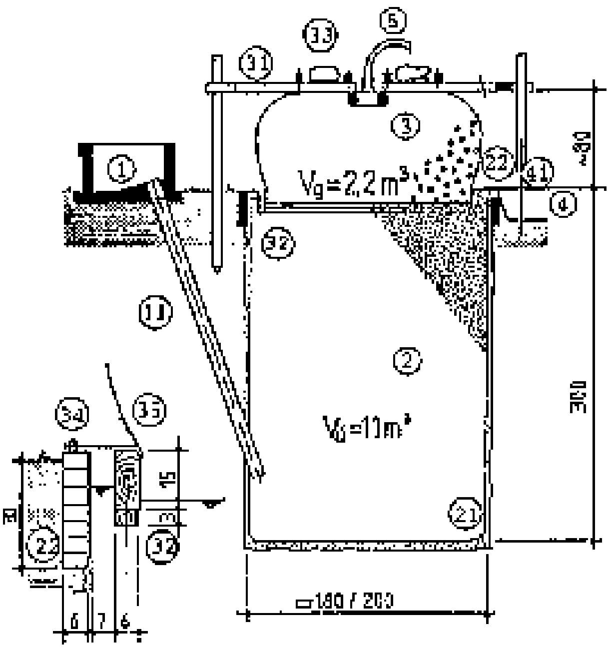

Figure 4: Earth pit biogas digester with plastic sheeting gasholder. 1. Mixing pit, ll Fill pipe, 2 Digester, 21 Rendering, 22 Peripheral masonry, 3 Plastic-sheet gasholder, 31 Cuide frame, 32 Wooden frame, 33 Weight, 34 Frame anchorage, 35 Plastic sheeting, 4 Slurry store, 41 Overflow, 5 Gas pipe (OEKOTOP in (Werner, Stöhr and Hees, 1989))

Increased biogas pressure can be achieved by weighing down the gasholder. The plant does not impose as immediate a risk of explosion as the fixed dome construction as the structure is not gas-tight (Werner, Stöhr and Hees, 1989) however appropriate design safety features for biogas handling must still be maintained.

2.4 Ferro-cement plant

Ferro-cement biogas digesters are cast-in-situ structures constructed using cement mortar with steel wire mesh layers (Council of Scientific & Industrial Research, 2007) (Figure 5). Ferro-cement digesters can be self-supporting singular or multiple compartment chambers or earth-lined pit chambers. The compartment chambers allow for the containment of the fermenting waste and biogas collection. Inlet and outlet piping are provided to facilitate entry of the waste to be fermented and removal of the digested sludge and biogas venting and piping is provided for access to the stored biogas.

The ferro-cement digester doesn't require high volumes of construction material however the required quality of cement for construction is high (i.e. ferrocement) (Polprasert, Nukulchai and Rajput, 1982). The constructing of the plant is theoretically easy in rural areas however a standardised method has not yet been adequately time-tested (Cheng et al., 2014). Careful handling of the ferro-cement structure is necessary during transport and construction to prevent damage, therefore the applicability of this technology is mostly recommended in communities where ferro-cement experience is present (Council of Scientific & Industrial Research, 2007).

Continuous daily operation yields a biogas production rate of 0.3 to 0.6 $m_{gas}{}^{3}m/m_{volume}{}^{3}$ (or 30 to 60% gas production efficiency) during operation, and digesters are typically sized between 4 to 20 m3. The operational lifetime of a ferro-cement plant ranges from 6 to 10 years (Werner, Stöhr and Hees, 1989). Scum accumulation can reduce gas production, which can be maintained by mixing and withdrawing portions of the slurry. Ferro-cement has a greater crack-proof property than regular cement, so the overall strength is high. The reliability of

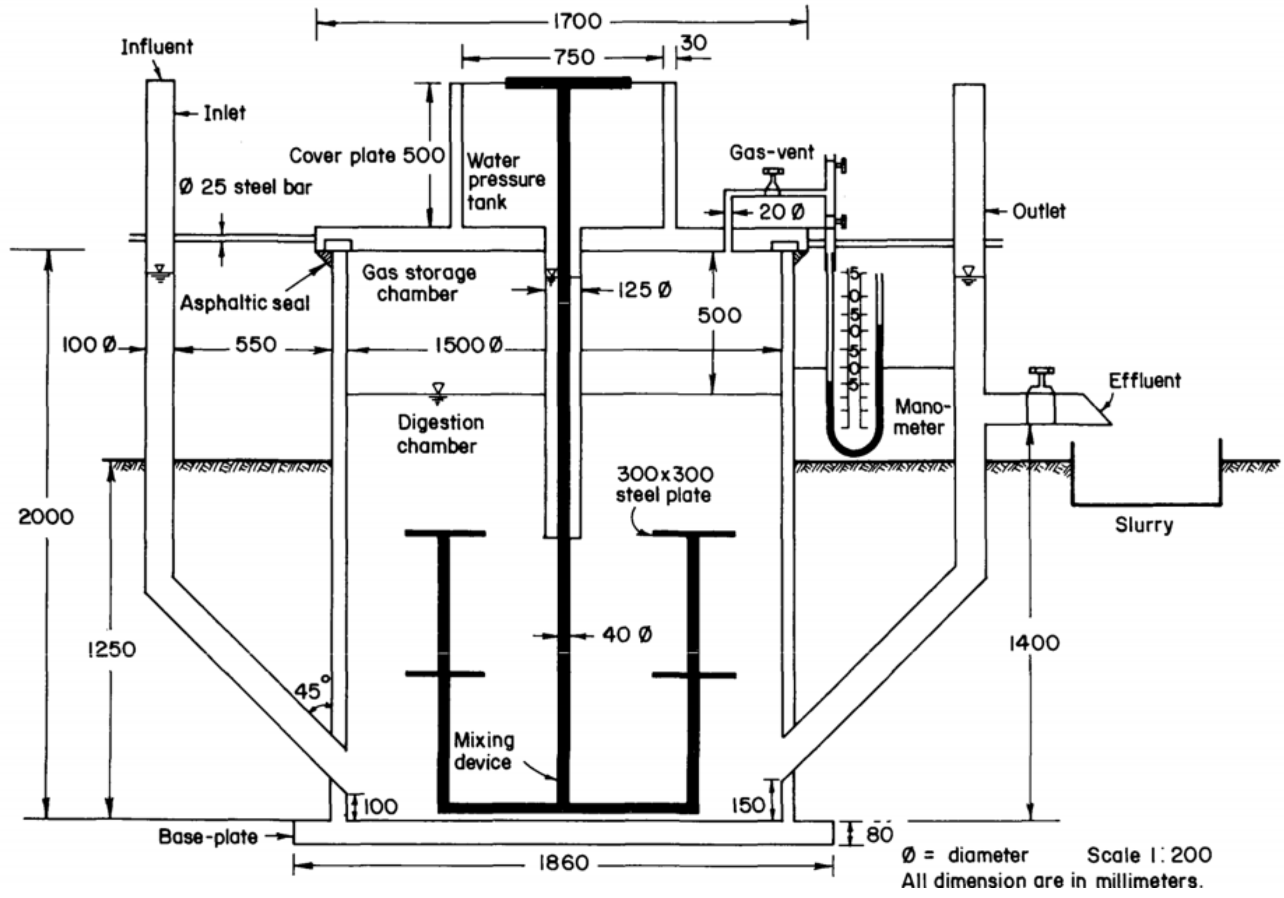

Figure 5: *Schematic of Ferro-cement biogas digester cross section Kanok-Nukulchai and Robles-Austriaco,* 1985)

the plant can be enhanced using an extra storage tank to prevent leakages and continually allow for production. The gasholder requires special sealing measures to prevent leakages, and excessive pressure could cause leakages at seals. However, ferro-cement seals are tighter than in regular cement, so leakages are expected to be lower than a fixed dome plant. Lastly, as there are no known explosions reported from the operation of ferro-cement biogas digesters, this type of construction can be considered to generate a lower risk of explosion than fixed dome plants. (Polprasert, Nukulchai and Rajput, 1982).

2.5 Bag digester

Bag digesters (also known as balloon digesters or low-cost polyethylene digesters) are long, cylindrical plastic bags placed into trenches, lined with compacted sand and mud (Kuria and Maringa, 2008) (Figure 6).

The cost of the bag is generally low (between $20 to $200 USD) though importation taxes for developing countries can double the cost. AS they are easy to transport, bag digesters are well suited for remote areas where construction materials are difficult to acquire and transport. In addition, bags are a good solution when the groundwater table is high as the plastic prevents seepage into or out of the digester. This is in contrast to masonry construction where wastewater seepage is more likely to occur; this is most problematic for areas with high groundwater tables where risk of groundwater contamination high (Cheng et al., 2014).

The bags are easy to install and do not require masonry expertise, but do require adequate waste to be added for the bag to provide sufficient pressure (Cheng et al., 2014). Where low pressure gas output is reported weights can be placed on bags to increase pressure. As air-tight seals are difficult to produce where the piping joins the bag despite the use of sealants, gas leakages are common. If gas production is high and the produced gas is not utilised or stored, the bags can explode (Kuria and Maringa, 2008).

The bag volume is typically 4 to 100 m3 with an expected lifetime between 2 to 5 years. Estimated daily output from digesters of this technology is 0.3 to 0.8 $m_{gas}{}^3 m/m_{volume}{}^3$ (or 30 to 80% gas production efficiency) (Werner, Stöhr and Hees, 1989).

The bag is simple to maintain with most repairs consisting of sealing works should the bag be damaged or ruptured. Sediment accumulation in the bag is very difficult to remove. The bag's structural integrity is low; the thin

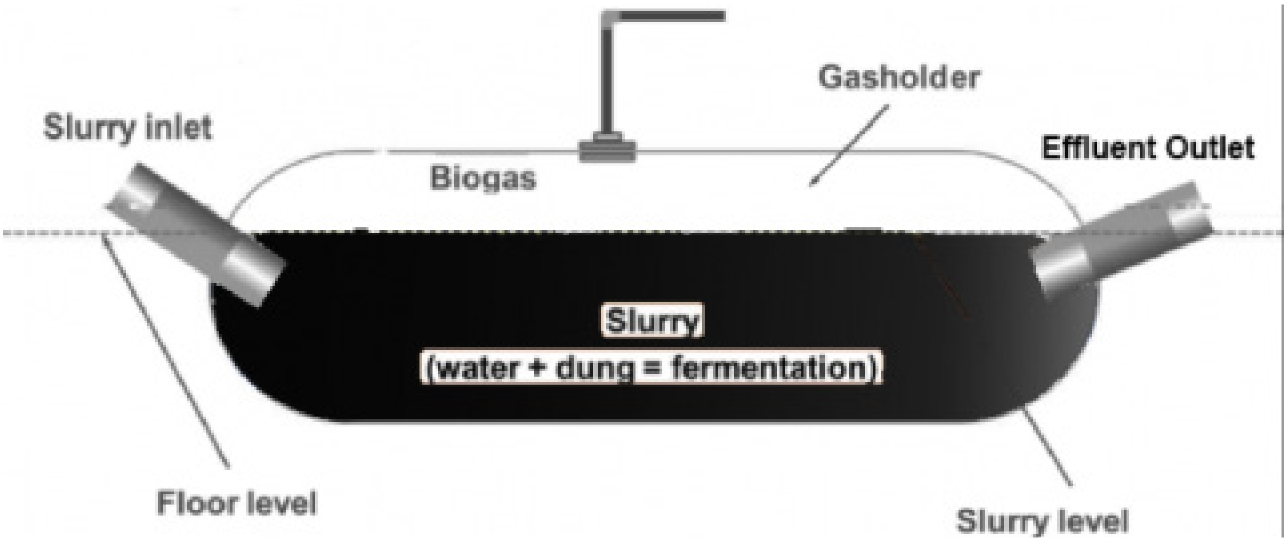

Figure 6: *Bag biogas digester schematic* (*Massachusetts Institute of Technology Impact Labs, n.d.*)

plastic used commercially to manufacture bags is prone to damage from falling objects, people and animals. The scope of this study did not consider non-traditional bag materials. This design requires shelter from direct sunlight and is impacted by changes in temperature, which in turn is dependent upon the material and its colour, and the resulting rates of heat transfer. The recommended mean temperature is greater than 20°C, so biogas production rates are poor during cold nights or winter.

2.6 Composite material digester

Composite material digesters are prefabricated and commonly used commercial technologies. Made of fiberglass, carbon fibre and polyester, they are mainly manufactured remotely and imported to remote and rural areas such as Tanzania. Composite digesters have high initial investment cost but do not require local masonry skill. A typical composite digester costs approximately $3,000 USD, which may be cost prohibitive in terms of upfront capital available, for example, at MBHS. The prefabricated designs are only available in select volumes.

Operation is theoretically simple, but a lack of operational guidelines can lead to significantly reduced working efficiency (Cheng et al., 2014). The typical operational lifetime of a composite digesters cannot be easily estimate as the lifetime varies based on the manufacturer and construction materials used, however, of the digester technologies reviewed in this study, the composite material digester is assumed to have the longest operational lifetime.

Composite material digesters have a high resistance to corrosion and are strong and durable, with the ability to hold consistently high gas pressures. To ensure proper operation, composite material digesters require technical and operational follow-up inspections post implementation, which is often lacking in remote and rural environments. Additionally, if the composite material digesters are manufactured locally in inexperienced manufacturing plants; the risk of producing malfunctioning low-quality digesters is greater. Composite material digesters are also prone to sinking into soft ground material. Seepage of wastewater into the groundwater table is minimised due to the tight sealing construction (Cheng et al., 2014).

2.7 Ratings for design criteria

In order to select an appropriate biogas digester design for MBHS, we used the technology review methodology developed as part of this study to evaluate each digester's strengths and weaknesses against the following ten (10) defined criteria:

1. *Strength* – Can the design withstand the gas pressure from the waste slurry?
2. *Cost* – What is the overall cost of materials, construction, training and ongoing maintenance?
3. *Materials* – Are materials locally available?
4. *Ease of Construction* – What level of skill is required for plant construction?
5. *Ease of Operation* – How easily will a local user be able to operate the plant?
6. *Ease of Maintenance* – What degree of maintenance will be regularly required?
7. *Reliability* – Can the plant consistently function as needed?
8. *Gas-tight* – Can the design withstand gas leakages?

9. *Safety* – Is it safe to operate the plant, both for the user's health and physical safety?

10. *Environment* – Can the plant withstand the local environmental conditions? What health impacts can the plant have on the local environment and people?

These criteria were developed based on Kuria's design factors (Kuria and Maringa, 2008). The criteria were selected to gauge the digesters' construction and operation in specific environmental conditions; in our case MBHS is a tropical and rainy climate where temperatures average 24.9°C, with average annual rainfall exceeding two (2) meters (Climate-Data.org, 2018).

Each digester is ranked over the criteria for the specific application of MBHS on a scale of one (1) to ten (10), with 1 being the lowest and 10 being the highest. We based the scores on evaluating the author's experience in the local environment and conversations with future plant users against the definition of each of the criteria across each digester design. In this study, each criterion was weighed equally, but in future investigations, it would be possible to weight the criteria based on the importance of each design and ease of operation in the local environmental context.

The scoring shows that the floating drum design is rated as the most effective design for MBHS. However, we recommend two design changes to further enhance the digester's suitability. Firstly, the digester should incorporate a water jacket so that the drum rises and falls within the water instead of the fermenting waste slurry (Figure 7). The jacket both enhances hygiene by removing operator contact with the waste slurry and prevents the drum from becoming stuck in the floating scum on the slurry surface. Secondly, a roofing structure (not shown) should be constructed over the plant to prevent rain from both diluting the slurry and causing corrosion. These modifications impact the plant's ease of operation, maintenance, safety, and applicability in the local environment whilst only adding slight cost. Reassessing the design with respect to the design criteria above, this would allow for at least a three-point increase in score from 76 to 79, with a decrease in one point in the "operation", "maintenance", "safety" and "environment" criteria and increase of one point in the "cost" criteria.

We began the design process by estimating the school's daily waste production, which is a function of the number of students and their daily toilet use. Waste estimates for students, all aged in their teens and twenties, were based on an adult producing an average 1.22 kg of waste per day (urine and faeces) (Fry, Merrill and Merrill, 1973). This estimate was used in modelling the boarding-students' (advanced-level) waste production. The waste of day students (ordinary-level) was estimated to be half of the

Table 1: *Ranking of the six most common biogas digesters over selected design criteria*

Design Criteria	***Fixed Dome***	***Floating Drum***	***Earth-Pit Plant***	***Ferro-Cement Plant***	***Bag Digester***	***Composite Material Digester***
Strength	8	8	7	8	5	9
Cost	7	6	8	7	8	4
Availability of materials	9	9	9	8	6	4
Ease of construction	5	8	8	5	6	4
Ease of operation	7	9	8	8	7	7
Ease of maintenance	5	7	7	6	5	7
Reliability	7	8	6	7	5	8
Gas-tight	6	7	6	7	5	8
Safety	5	8	7	7	7	9
Environment	8	6	6	8	8	7
TOTALS	67	76	72	71	62	67

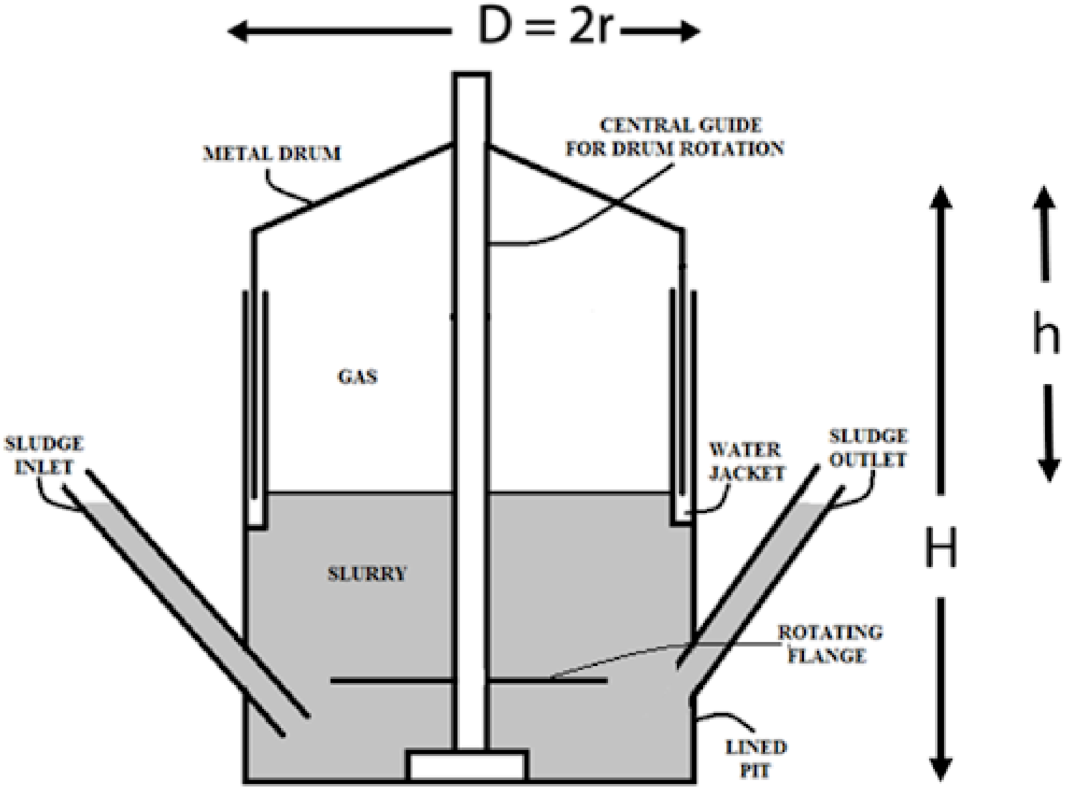

Figure 7: Schematic of the modified floating drum biogas digester (not to scale)

advanced-level student daily average, based on the proportion of time spent at school (6:30AM to 5:00PM). These assumptions are limited as they do not reflect diet or environmental factors; capturing local data on waste production was outside the scope of this research.

The students were then assigned to the bathroom that they predominantly use to estimate the daily waste flow to each septic tank. Only the bathrooms at elevations higher than the anticipated digester location would be incorporated into the system design to eliminate the need for a pump. Inclusion of pumps in this design was deemed unfeasible due to inconsistent electricity supply in the local village and high maintenance requirements and low resource abilities (both technical expertise and good sanitary practice) to service the maintenance requirements. Inclusion of generators for electricity production was deemed cost prohibitive both from a capital and operational perspective owning to high costs of petrol and lack of local access to petrol. The proposed biogas digester location and bathroom locations are labelled on the campus map in Figure 8.

The distance and change in elevation between each bathroom and the plant location were determined using a Garmin GPSMAP 64ST (Garmin Ltd., 2016). The slope was calculated for each pipe route and when compared to the International Plumbing Code, we saw that each value exceeded the code's recommendation for horizontal drainage pipes (2015 International Plumbing Code, 2015). Therefore, the locally available pipe was found able to accommodate the flow, and intermediate pumps or tanks were not deemed necessary.

The North Bathrooms were associated with dormitories, the Central Bathrooms accommodated dormitory students and a limited number of day students, and the East Bathrooms were used by a dormitory of students, and all female students. To include multiple design sizes based on varied daily waste production, the bathrooms were considered independently, grouped in combinations, and grouped together in each of the design calculations. The calculations made for MBHS biogas digester can be found into Table A1 to Table A5 in APPENDIX A.

3 DESIGN RESULTS

3.1 Sizing the digester

One of the important parameters for digester sizing is the hydraulic residence time. The hydraulic residence time is the average time the waste spends inside the digestion vessel. The hydraulic residence time is correlated to two parameters: the digester volume and the organic loading rate as shown in Equation 1. The organic loading rate is defined as the amount of waste fed to the system on a daily basis (Kuria and Maringa, 2008).

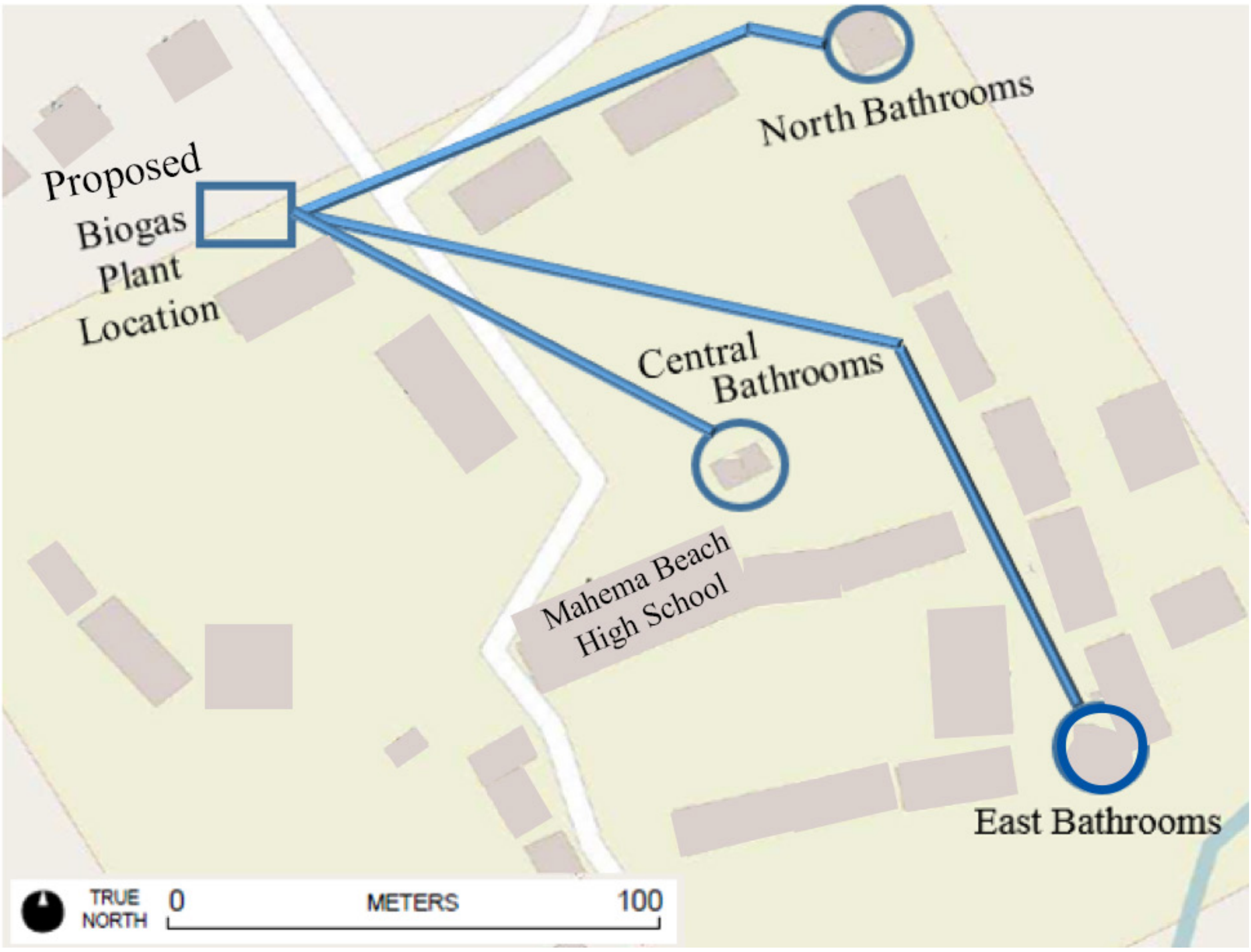

Figure 8: *Bathroom and proposed biogas digester locations on MBHS's campus with piping routes. Note*: (*This map was created using fieldpapers.org, an open-source tool to create atlases from Google Maps.*)

$$R = \frac{V_d}{v} \tag{1}$$

where:

R = Hydraulic retention time [days]

V_d = Digester volume [m^3]

v = Organic loading rate [m^3/d]

Recommendations for design retention time vary, but 100 days is strongly recommended for human excreta to ensure the safety of operators when removing the waste from the digester (Khatavkar and Matthews, 2013).

To determine the impact of retention time on scale and cost, a design retention time of 20 to 100 days is used. Combining the estimated production of 1.22 kg of human waste (faeces and urine) per person per day and assuming a density of approximately 1,000 kg/m3 for human waste slurry (Onojo et al., 2013) allowed us to calculate the organic loading rate of (v) (m3/day). The basic equations used in our analysis are presented here. Further details and calculations are found in APPENDIX A.

After the required volume is determined, the dimensions of the digester can be calculated. Based on the literature of floating drum designs, the volume of the digester is approximated as a cylinder, with the diameter of the digester (D) (m) is assumed to be equal to the height (H) (m) (Kuria and Maringa, 2008). Equation 2 below represents volume as a function of the diameter (D) only. Equation 3 shows the rearrangement of Equation 2 to solve for diameter.

$$V_d = \frac{\pi D^2 H}{4} = \frac{\pi D^3}{4} \tag{2}$$

$$D = \sqrt[3]{\frac{4V_d}{\pi}} \tag{3}$$

3.2 Estimating the cost

A limiting factor for project feasibility is the construction cost, which is predominantly related to the cost of steel and piping.

The cost of construction was calculated to determine the initial, limiting investment that would be required to develop the biogas digester. For the purposes of this assessment, the maintenance cost is treated as an ongoing system cost and not an influencing factor for initial investment requirements.

The cost of steel is a direct function of the digester surface area and unit price of material. Given the radius of a metal drum r=D/2 and the assumption that the metal drum height (h) is approximately one half of the total masonry digester height (H) (Figure 7), we can calculate the area of steel required (Equation 4), assuming the digester can be approximated as a flat-topped drum. The local cost per square meter (m^2) of steel is used to determine the total cost of the drum.

$$Surface\ Area = 2\pi rh + r^2 \quad (4)$$
$$= 2\pi\left(\frac{D}{2}\right)\left(\frac{H}{2}\right) + \pi\left(\frac{D}{2}\right)^2$$
$$= 3\pi\left(\frac{D^2}{4}\right)$$

We designed the pipe routes to be as direct as possible and limited unnecessary pipe bends to minimise interference with existing structures on campus (Figure 8). The total piping cost was calculated from the total design length of the piping and the local cost per metre of material.

3.3 Comparing estimated cost and plant outputs

We compared the two major cost components with the plant outputs to evaluate economic feasibility. The primary plant outputs are: total daily biogas yield, the equivalent number of meals made with the gas produced, the equivalent mass of firewood saved per day, the time saved spent collecting firewood.

The daily gas yield is a function of the average gas yield per kilogram of human excreta [m^3/kg] (Werner, Stöhr and Hees, 1989), the mass of excreta produced daily by students [kg/person], and the number of students at school. In the scope of this study, the gas yield rate was assumed to be constant. Based on Oxfam's research on biogas yield from human excreta, we chose a value of 0.02 m^3 gas per kilogram human excreta (Oxfam, 2008).

The equivalent meal numbers produced is calculated from the total daily biogas yield assuming a certain volume of biogas consumption per meal generated. We utilised Oxfam's biogas generator design research value of 0.3 m^3 of biogas required per meal generated (Oxfam, 2011).

The equivalent firewood saving was determined we compared the energy content of biogas to that of firewood (Werner, Stöhr and Hees, 1989). The time saved from firewood collection by using biogas as cook fuel was calculated by using research on wood collection times in Southern Tanzania (Preston, 2012). Based on Preston's (2012) data on hours spent collecting firewood per year and mass collected per year, we estimate the average rate of firewood collection to be 8.2 kg per hour.

Plant outputs for each of the MBHS's bathroom waste-input combinations were calculated. The results of these calculations can be found in APPENDIX A.

4 DISCUSSION

The feasibility study suggested that the floating drum biogas digester would be the most suitable design for the school based on its safety during operation (both physical and with regards to sanitation) and the current lack of multi-year biogas management experience at the school. We recognise that education and training would be required should any biogas digester system be installed, but did prioritise ease of entry to technology adoption in our evaluation process.

The major costs in constructing this type of plant include: the material costs of the steel used for the digester drum and the piping connecting the septic tanks to the digester. If the recommended retention time of 100 days is employed, the digester would range in volume from 12 to 60 m^3, depending on the number of septic tanks that are connected. The cost of the two major components would range from approximately $3,000 to $10,000 USD, which does not include continual operating or maintenance costs. Operating costs include personnel supervision and monitoring of the plant; maintenance costs would include cleaning and repairs of the digester and drum, and slurry removal and disposal as necessary.

It is estimated that a plant of this configuration would yield approximately 2 to 12 m^3 biogas daily. This volume of biogas corresponds to approximately: 8 to 40 meals cooked, 3 to 16 kg firewood saved, and 0.4 to 2 hours per day of time gained from not requiring firewood collection. Given the largest design (with all septic tanks connected) the biogas produced would not be able to replace cooking with firewood completely, but would serve as a useful supplementary fuel.

5 CULTURAL CONSIDERATIONS

Prior to developing a biogas project, it is important to understand how the fuel generated will be perceived locally, particularly if considering the use of human excreta as feedstock. If this practice is new to a community, it is important to acknowledge that a simplified characterisation of biogas digester processes is essentially "cooking with human waste," which can be seen as unclean and undesirable. The acceptance of such a practice can be opposed by cultural barriers related to social stigma, religion, health practices and institutional knowledge (Mittal, Ahlgren and Shukla, 2018).

Even with an optimal and well-functioning biogas digester design , cultural barriers can prevent plant operation from succeeding. Lee et al. (2013) studied technology adoption in cultures that varied in terms of degrees of collectivism. Lee at al. noted for effective diffusion of technology there is a relationship between cultural values and the importance of the level of perceived innovation versus the level of positive subjective evaluations of the technology by peers (Lee, Trimi and Kim, 2013). Since Tanzania is considered a collectivistic society, positive subjective evaluations by peers, or the opportunity to see others adopting and liking anaerobic biodigester designs, are necessary for effective adoption of such systems (Hofstede, 2015). Thus, it is important to know if existing biogas infrastructure can be found locally and how people perceive different waste materials as fuel. For a biogas project to successfully move forward, it is critical to provide appropriate communication and education centred on how the plant operates hygienically and how biogas is a clean cooking fuel.

6 CONCLUSION

The biogas digester design process shows that the plant at MBHS would have a high initial cost of construction, even without incorporating the costs of additional materials, labour, and transportation. The high costs are a function of the local prices of steel and piping and the large spread of the school's campus. The biogas yield produced would not be sufficient to entirely replace cooking with firewood, so biogas would most likely only serve as a supplementary cooking fuel.

Given a current lack of biogas management experience at the school, it would be difficult to both ensure proper maintenance and to rationalise the initial investments needed for the project, especially when other projects (such as dormitory and classroom construction) have already been prioritised in the school's expansion budget. The prohibitive costs are partly associated with the specific floating drum design, but this type of digester was prioritised in part because of the sanitary measures it employs; we did not feel that installing fencing around a biodigester was sufficient for our level of risk tolerance. As a biodigester at MBHS would be operated in a school environment with approximately 1,000 students present, it would be unethical to recommend a system that could potentially increase the health risk on campus, for example, by contaminating water sources.

Although the use of a biogas digester for fuel production is not ideal for this specific school setting, it could be feasible in alternative environments. Key factors that influence the feasibility are the proximity of toilets (less piping is required if they are grouped more closely together), availability and cost of steel, and demand for biogas (based on the number of people supported by cooking). For instance, in a hospital or health clinic setting, the buildings include more densely located toilets with many outpatients who use these facilities but are not fed on-site. The inpatient population that would be served meals would be a smaller fraction of the total waste-producers, so cooking with firewood could potentially be replaced entirely. We do note that the installation of any type of biogas digester would require training for operation and maintenance to ensure that users are working with a safe and sanitary energy source.

Future work to further develop this methodology could relate to developing case studies around designs of the other types of digesters. It would be helpful to collate more detailed cost estimation procedures for all types of digesters, for example including the additional cost of training for operation and maintenance of the digesters. Such level of detail is beyond our current scope.

The barriers to cultural acceptance of biogas digesters should be further investigated as they will vary dependent on the specific community and culture in which the plant would be employed. These cultural considerations are extremely important with regards to community cooperation and endorsement and should not be overlooked.

7 ACKNOWLEDGEMENTS

Thanks to Matema Beach High School's students, teachers and staff for collaborating to develop this research initiative, specifically Headmaster Solomon Mwaipopo and Richardson's project counterparts: Kava Ilombo and Gertruda Ruhele. The Peace Corps community in Tanzania provided continual support throughout my service, and special thanks are given to Oregon State University's School of Mechanical, Industrial and Manufacturing Engineering for their support of the Peace

Corps Master's International program and my research both on campus and abroad.

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9 APPENDIX A

Table A1: Calculations of the organic loading rate into the biogas digester

Parameter	Bathroom						
	North	***Central***	***East***	***North & Central***	***North & East***	***Central & East***	***All***
# Advanced-Level students	280	10	70	190	250	80	260
# Ordinary-Level students	0	170	280	170	280	450	450
(A-level student waste)/day m3				0.00122			
(O-level student waste)/day) m^3				0.00061			
Organic loading rate, v, m^3/day	0.22	0.12	0.26	0.34	0.48	0.37	0.59
Daily mass of waste [kg]	220	120	260	240	480	370	590

Equations used:

$$\textit{Organic loading rate, } v\ [m^3/day] = (\textit{No. of A-level students}) \times (\textit{Daily waste per A-level student}) + (\textit{O-level students}) \times (\textit{Daily waste per O-level student}) \quad (A1)$$

Note: daily waste per person estimated as 1.22 kg (Fry, Merrill and Merrill, 1973); density of human slurry estimated as 1,000 kg/m^3 (Onojo et al., 2013)

Table A2: Calculations of the necessary digester volume as a function of desired retention time

Parameter	Bathroom						
	North	***Central***	***East***	***North & Central***	***North & East***	***Central & East***	***All***
$V_{d,1}$ at R = 20 days [m^3]	4.39	2.32	5.12	6.71	9.52	7.44	11.83
$V_{d,2}$ at R = 40 days [m^3]	8.78	4.64	10.25	13.42	19.03	14.88	23.67
$V_{d,3}$ at R = 60 days [m^3]	13.18	6.95	15.37	20.13	28.55	22.33	35.50
$V_{d,4}$ at R = 80 days [m^3]	17.57	9.27	20.50	26.84	38.06	29.77	47.34
$V_{d,5}$ at R = 100 days [m^3]	21.96	11.59	25.62	33.55	47.58	37.21	59.17
H_1, D_1 [m]	1.77	1.43	1.87	2.04	2.30	2.12	2.47
H_2, D_2 [m]	2.24	1.81	2.35	2.58	2.89	2.67	3.11
H_3, D_3 [m]	2.56	2.07	2.69	2.95	3.31	3.05	3.56
H_4, D_4 [m]	2.82	2.28	2.97	3.25	3.65	3.36	3.92
H_5, D_5 [m]	3.04	2.45	3.20	3.50	3.93	3.62	4.22

Equations used:

$$volume\ [m^3] = (No.\ of\ days\ for\ retention) \times (Organic\ loading\ rate) \tag{A2}$$

$$H_x, D_x = \sqrt[3]{\frac{4 \times volume}{\pi}} \tag{A3}$$

Table A3: *Costing calculations for the piping and steel required to construct a floating drum digester*

Parameter	**Bathroom**						
	North	***Central***	***East***	***North & Central***	***North & East***	***Central & East***	***All***
Length of piping needed [m]	106	85	200	190	306	285	391
Unit cost of piping [$/m]				$3			
Cost of piping [$]	$318	$255	$600	$573	$918	$855	$1,173
Amount of steel needed for drum 1 [m²]	7.42	4.85	8.23	9.85	12.43	10.55	14.37
Amount of steel needed for drum 2 [m²]	11.78	7.70	13.06	15.63	19.73	16.75	22.82
Amount of steel needed for drum 3 [m²]	15.44	10.08	17.11	20.48	25.85	21.95	29.90
Amount of steel needed for drum 4 [m²]	18.71	12.22	20.73	24.81	31.32	26.59	36.22
Amount of steel needed for drum 5 [m²]	21.71	14.18	24.05	28.79	36.34	30.85	42.03
Cost per unit steel [$/m²]				$200			
Cost for the drum 1 [$]	$1,485	$970	$1,645	$1,969	$2,486	$2,110	$2,875
Cost for the drum 2 [$]	$2,357	$1,539	$2,612	$3,126	$3,946	$3,350	$4,563
Cost for the drum 3 [$]	$3,088	$2,017	$3,422	$4,096	$5,171	$4,389	$5,980
Cost for the drum 4 [$]	$3,741	$2,443	$4,146	$4,962	$6,264	$5,317	$7,244
Cost for the drum 5 [$]	$4,341	$2,835	$4,811	$5,758	$7,269	$6,170	$8,406
Total cost 1 [$]	$1,803	$1,225	$2,245	$2,542	$3,404	$2,965	$4,048
Total cost 2 [$]	$2,675	$1,794	$3,212	$3,699	$4,864	$4,205	$5,736
Total cost 3 [$]	$3,406	$2,272	$4,022	$4,669	$6,089	$5,244	$7,153
Total cost 4 [$]	$4,059	$2,698	$4,746	$5,535	$7,182	$6,172	$8,417
Total cost 5 [$]	$4,659	$3,090	$5,411	$6,331	$8,187	$7,025	$9,579

Equations used:

$$Cost\ of\ piping\ [\$] = (Length\ needed) \times (Unit\ cost\ per\ length)$$

$$Steel\ needed\ for\ drum\ [m^2] = 3\pi \times (diameter\ of\ digester)^2 \div 4;\ top\ assumed\ to\ be\ flat \tag{A4}$$

$$Cost\ of\ steel\ drum\ [\$] = (Steel\ needed\ for\ drum) \times (Unit\ cost\ of\ steel) \tag{A5}$$

$$Total\ cost\ [\$] = (Cost\ of\ piping) + (Cost\ of\ steel\ drum) \tag{A6}$$

(A7)

Table A4: Comparison of the energy content of biogas versus firewood

Fuel Type	**Energy Content (MJ)**	**Per unit measure**
Biogas	25	1 m^3
Wood	19	1 kg

Equations used:

$$\textit{Equivalent mass of firewood } [kg] = 25 \div 19 \times (\textit{Volume of biogas})\ [m^3] \tag{A8}$$

Table A5: Calculations of the effectiveness of the biogas digester: gas volume, equivalent meals, and time saved

Parameter	**Bathroom**						
	North	***Central***	***East***	***North & Central***	***North & East***	***Central & East***	***All***
Gas yield per day [m^3]	4.4	2.4	5.2	6.8	9.6	7.4	11.8
Estimate meals cooked with gas	14.7	8.0	17.3	22.7	32.0	24.7	39.3
Equivalent mass of firewood per day [kg]	5.8	3.2	6.8	8.9	12.6	9.7	15.5
Time saved (based on equivalent mass) [hour]	0.7	0.4	0.8	1.1	1.5	1.2	1.9

Equations used:

$$\textit{Gas yield per day } [m^3] = 0.02 \times (\textit{Daily mass of human waste})\ [kg] \tag{A9}$$

$$\textit{Estimated meals made with gas} = (\textit{Gas yield per day}) \div 0.03\ [m^3] \tag{A10}$$

$$\textit{Time saved } [hour] = (\textit{Equivalent mass of firewood}) \div 8.2\ [kg/hr] \tag{A11}$$

Development and External Validation of a Logistic Regression Derived Algorithm to Estimate a Twelve-Month Open Defecation-Free Status

Warren Mukelabai Simangolwa[1]*
[1] Independent Health Economist
Lusaka, Zambia
Email: mukewarren@gmail.com

*corresponding author

ABSTRACT: *Appropriate open defecation free (ODF) sustainability interventions are key to mobilising communities to consume sanitation and hygiene products and services that enhance quality of life and result in embedded behavioural change. This study aims to develop a logistic regression derived risk algorithm to estimate the risk of the loss of ODF status over a 12-month period, and to externally validate the model using an independent data set. ODF status loss occurs when one or more toilet adequacy parameters is no longer present for one or more toilets in a community. Data collected in the Zambia district health information software for water sanitation and hygiene management was utilised in this study. Datasets for the Chungu and Chabula chiefdoms were selected for this study. The data was collected from the date of attainment of ODF status (October 2016) for a period of 12 months until September 2017. The Chungu chiefdom data set was utilised as the development data set whilst the Chabula chiefdom data set was utilised as the validation data set. Data was assumed to be missing at random and the complete case analysis approach was used. The events per variables were satisfactory for both the development and validation data sets. Multivariable regression with a backwards selection procedure was used to decide candidate predictor variables with p values less than 0.05 meriting inclusion. To correct for optimism, the study compared amount of heuristic shrinkage by comparing the model's apparent C-statistic to the C-statistic computed by non-parametric bootstrap resampling. In the resulting model, an increase in the covariates 'months after ODF attainment', 'village population' and 'latrine built after CLTS', were all associated with a higher probability of ODF status loss. Conversely, an increase in the covariate 'presence of a handwashing station with soap', was associated with reduced probability of ODF status loss. The predictive performance of the model was improved by the heuristic shrinkage factor of 0.988. The external validation test confirmed good prediction performance with an area of 0.85 under the receiver operating characteristic curve and no significant lack of fit (Hosmer-Lemeshow test: p = 0.246). The results of this study must be interpreted with caution in context where ODF definitions, cultural and other factors are different from those described in the study.*

KEYWORDS: *Chiefdom, community-led total sanitation (CLTS), District Health Information Software (DHIS2), Prognostic model, open defecation free (ODF)*

1 BACKGROUND

Achieving and sustaining open defecation free (ODF) status has increasingly become a shared goal for communities, interventionists, non-governmental and the Government of Zambia. Poor access to sanitation and hygiene infrastructure negatively impacts progress on agreed international targets on health, poverty and human dignity (Roche, et al., 2017; Hutton & Chase, 2016).

In 2015, only 39% of the global population used safely-managed sanitation measures, with two in every five persons living in rural areas. As of 2015, 892 million people worldwide still practice open defecation (World Health Organization , 2017). The diseases associated with poor sanitation practice (including open defecation) account for about 10% of the global burden of disease (Prüss-Üstün, et al., 2008; McGinnis, et al., 2017). These include diarrhoeal diseases, acute respiratory infections, malnutrition and tropical diseases such as helminth and schistosomiasis infection (Van Minh & Hung, 2011; Araujo Navas, et al., 2016). Diarrhoea alone accounted for 19% of the deaths in children under the age of five in Sub-Saharan Africa (Mara, et al., 2010). 88% of these cases are attributable to unsafe water, inadequate sanitation, and poor hygiene (Roche, et al., 2017). The lack of access to safe sanitation cost the global economy USD $222.9 billion in 2015, with associated costs linked to mortality, productivity and healthcare (Lixil, WaterAid Japan & Oxford Economics, 2016). The global economic return on sanitation spending is USD $5.5 per US dollar invested (Hutton, 2012).

The key to mobilising communities to move away from poor sanitation practices, such as open defecation, is the use of appropriate sustainability interventions otherwise termed 'Open Defecation Free' (ODF) measures. One such measure is the adoption of "adequate household toilets". An adequate household toilet is one that satisfies the following design requirements: 1) contains a smooth cleanable floor, 2) has a superstructure that provides privacy, 3) includes a handwashing station with soap and, 4) has a lid or vent valve to prevent flies.

A community, such as a chiefdom, can be designed an Open Defecation Free (ODF) status when all of the household in every village contain an adequate household toilet. If not every village in the chiefdom contains adequate toilets; the chiefdom is designated with an open defecation (OD) status.

Once ODF status is granted through verification and certification, this status must be maintained by the community through ongoing maintenance of existing adequate household toilets as well as the construction of new adequate household toilets. The ODF status is not a permanently held status and can be lost or reverted when one or more of the adequacy parameters are no longer present for one or more toilets in a community (Galan, et al., 2013; Njuguna & Muruka, 2017): this trend is otherwise termed ODF status loss.

It is recognised that maintaining the ODF status is challenging due to uncertainties in social cohesion, d and government prioritisation of sanitation, sustainability of toilet and handwashing technologies, sanitation financing, governance, monitoring and sanitation markets (Bongartz, 2016; Odagiri, et al., 2017). Faced with the challenge of ODF status loss, there is limited scientific evidence to guide a systematic approach on mitigating ODF status loss risk factors.

ODF status loss risk prediction can be useful in guiding and subsequently inform the adoption of cost-effective and timely mitigation measures. (Hendriksen, et al., 2013). A risk score is a standardised metric for the likelihood that a variable of interest will experience an outcome (Royston, et al., 2009). ODF status loss risk prediction modelling is essential in identifying and providing appropriate intervention measures for communities at high risk of ODF status loss.

This paper aims to develop a simple systematic tool to identify villages at high risk of ODF status loss. It develops and externally validates a prognostic model to estimate twelve-month status loss risk for a Zambian chiefdom. Equipped with this information, decision-makers can more wisely prioritise and allocate scarce human, financial, logistical and other associated resources for ODF sustainability interventions.

2 MATERIALS AND METHODS

2.1 Source of Data

In Zambia, for a chiefdom to be designated an ODF status, it must be verified and certified that all the chiefdom villages households include an adequate household toilet (Zimba, et al., 2016). The four design parameters that define an adequate household toilet are the following:

1. a smooth cleanable floor
2. a super structure providing privacy
3. a hand washing station containing soap and

an orifice lid Retrospective longitudinal cohort data was extracted from the district health information software for water sanitation and hygiene management information system (DHIS2 WASH MIS) registry data for both the development and validation data sets.

DHIS2 is a free and open-source framework for management of aggregated health information (Manoj, 2013). The DHIS2 is used for collection, validation, analysis, and presentation of aggregate statistical data, tailored to integrated health management activities (Asangansi, 2012). In Zambia, the DHIS2 serves as the national database platform for the Ministry of Local Government and Housing (MLGH) (Biemba, et al., 2017). The DHIS2 WASH MIS is a mobile surveillance real time monitoring tool that is used for sanitation and hygiene monitoring in Zambia (Markle, et al., 2017).

Data in the DHIS2 WASH MIS is entered via a Java-supported mobile phone by community volunteers (community champions). The volunteers are tasked with providing monthly data monitoring support for village groups averaging 10 villages or more. The community volunteer amalgamates data collected from each village's sanitation action group (SAG). The village SAG is responsible for collecting paper-based household level data on parameters related to toilets. They use the water sanitation and hygiene, sanitation action group (WASH SAG) data collection form. Each community champion visits their assigned villages of supervision, during the period from first to the tenth of each month. They are expected to collect and submit aggregated data from each village's WASH SAG data collection form for the previous month by the tenth day of each month. Before the community champion aggregates data and submits through their mobile phone, they randomly pick three households on the WASH SAG form for a spot verification check. A ward government line agency extension officer, conducts a meeting with a champion to assess the quality of the data prior to submission to the DHIS2WAS MIS platform. The following variables are collected from utilising the WASH SAG data collection form: village name, total number of households in a village, village population, number of toilets before and after Community-Led Total Sanitation (CLTS) approaches were implemented, number of toilets fulfilling the adequate household toilet definition.

2.2 Interventions and Village Selection

The Chungu and Chabula chiefdoms were utilised as the development and validation datasets for this study. Data for both these chiefdoms was extracted from the DHIS2 WASH MIS platform. Chungu and Chabula chiefdoms are two of the five chiefdoms in the Luwingu district of the Northern Province of Zambia.

Sanitation and hygiene interventions were introduced in the two chiefdoms in August 2014 through the local district council with support from its sanitation and hygiene partners. The Community-Led Total Sanitation (CLTS) approach was used for sanitation demand creation in both Chungu and Chabula chiefdoms. CLTS is designed to mobilise individuals in action to eliminate open defecation as a whole community (Harter, et al., 2018). It is a participatory approach in which facilitators visit villages and trigger awareness of sanitation practices and subsequently perform follow-up visits to villages to generate a community-wide effort to become an open defecation free (ODF) status holder (Crocker, et al., 2017).

To build capacity of CLTS facilitators in implementing district-wide activities in Luwingu district, CLTS district and sub-district level implementers ere trained in the CLTS methodology through the District Water Sanitation and Hygiene Education Committee (DWASHE) with the assistance of the CLTS national coaches. The cadres were periodically followed up to review their application of CLTS methodology. The DWASHE is a multi-stakeholder representative body for all government line agencies, donors, local non-governmental organisations (NGOs), civil society organisations and the private sectors involved in the governance and implementation of sanitation interventions at district level (Lungu & Harvey, 2009; Kanyamuna, 2010). To steer quality and effectiveness in implementation targets, strategies, standards, norms and approaches were aligned through the development and use of the Luwingu District Total Sanitation Plan 2014 to 2017 through a multi-stakeholder process. All trained cadres at district and sub-district level were trained in the use of the DHIS2 WASH MIS platform and provided with Java-supported phones, WASH SAG data forms and bicycles to enhance effectiveness in reporting. The baseline data in 2014 revealed that 38% of the population in the Luwingu district had access to toilets whereas 0% had a handwashing station with soap (SNV, 2018).

Chief Chungu and Chabula's chiefdoms were sampled to determine their ODF status on the 20th of October 2016 (Mutyoka & Makombo, 2016; Kachemba, 2016). The Chungu chiefdom is led by her Royal Highness Chieftainess Chungu and is located 58 kilometres from the Luwingu district administration. The Chiefdom has a population

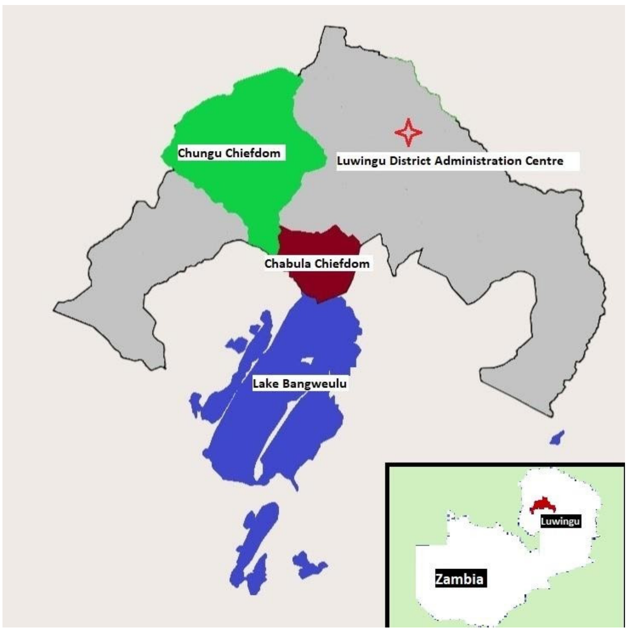

Figure 1: Location of Chungu and Chabula Chiefdom's in Zambia

of 29,840 people across 220 villages; 34 villages in Kampemba, 42 villages in Kafinsa, 38 villages in Ilambo, 52 villages in Mufili and 54 villages in Mulalashi wards (Central Stattistics Office , 2010). Villages are organised, small local communities of people in daily face-to-face interaction (Drennan & Peterson, 2006). The economy for the Chungu chiefdom is agricultural, with maize as the major cash crop.

The Chabula chiefdom is led by chief Chabula and is located 85 kilometres from the Luwingu district administration. The chiefdom has a population of 14,112 people across 117 villages; 79 villages in the Bwalinde and 33 villages in Ibale wards (Central Stattistics Office, 2010). The Chabula chiefdom's economy is a mix of agriculture and fish farming. The chiefdom borders Lake Bangweulu at Nsombo, a principal town at the northern part of the lake, which supports fish farming (Wikipedia contributors, 2018). Figure 1 shows the location of Chief Chungu and Chief Chabula chiefdoms.

The village population data collected for the development model includes 67 villages of 220 villages assigned to the Ilambo, and Mufili wards in Chungu chiefdom. In the validation dataset of the Chabula chiefdom, the village population data for 56 of the total 117 villages in the Bwalinde and Ibale wards were used.

To be included for both the development and validation datasets, only the villages that had data imputed for at least 3 of the 12 months of the year (i.e. at least 25%) were considered. There are no agreed estimates in literature on the amount of allowable missing data. Differing views are held by researchers on the appropriate cut-off point for data missingness but there have been suggestions as high as 20% is appropriate (Chao-Ying Joanne, et al., 2006). Table 1 shows the data captured for the study.

2.3 Outcome

The measured outcome in both the development and validation models, was ODF status loss. The ODF status loss variable in each village was derived by subtracting the monthly number of adequate toilets from the total monthly number of households in the village. Any non-zero result was assumed as an ODF status loss.

2.4 Predictors

The development and validation datasets were cleansed to ensure that the number of households in a village was always greater than or equal to the number of toilets defined as "adequate". Four cases with this inconsistency were retrieved and evaluated. The study investigated historical cases to ensure the data cleansing minimised the introduction of any new data.

The following predicator variables were extracted for each village: 1) Champion and SAG meeting, 2) latrine in use, 3) latrine built after CLTS, 4) latrine lids and, 5) latrine with smooth and cleanable floor data. Other predicator variables include: 1) latrine privacy, 2) number of latrines with handwashing with soap stations, 3) number of households and, 4) total village population. These predicator variables and co-variates are defined as

Table 1 *Village selection for the development and validation models*

Chiefdom	***Ward***	***Total number of villages***	***Villages with data***	***Villages without data***	***Villages with at least* 3 *month of data***
Chungu	Kampemba	34	0	34	0
	Kanfisa	42	7	35	0
	Ilambo	38	37	1	37
	Mufili	52	30	22	30
	Mulalashi	54	15	39	0
Total		220	90	131	67
Chabula	Bwalinde	79	67	12	23
	Ibale	33	33	0	33
Total		117	87	30	56

following:

- *Champion and SAG meeting* - the monthly number of interactions the community volunteer has with SAG.
- *Latrine in use* - the toilet infrastructure available in the village that are used as toilets
- *Latrine built after CLTS* - the number of latrines built after the CLTS intervention in each village.
- *Latrine lid* – ascertains the vector transmission of faecal matter.
- *Latrine with smooth cleanable floor* – ascertains the technologies to enhance use and maintenance of toilet facilities
- *Latrine privacy* - assesses acceptable latrine infrastructure (i.e. latrine walls, door etc.) that ensures dignity for users.
- *Number of latrines with handwashing with soap stations* – quantifies behavioural change through a proxy measure of the availability of a handwashing station with soap within 10 meters from a toilet.

2.5 Sample Size

The study did not calculate a formal sample size but used all available data in the development and validation models from the DHIS2 WASH MIS data to maximise the power and generalisability of the results. There are no generally accepted approaches to estimate sample size in the derivation and validation of studies for risk prediction models. Some have suggested having at least 10 events per candidate variable (EPV) for the derivation of a model (Pavlou, et al., 2015). The EPV for both the development and validation models for this study were satisfactory (Austin, et al., 2017; Vittinghoff & McCulloch, 2007) and therefore expected to provide estimates that are robust.

2.6 Missing Data

Limitations to data capture and reporting included the following: limited internet connection, loss of software application (DHIS2 WASH MIS) on mobile phones, failure to access villages during the wet season. As a consequence of these limitations, 12% of the development model data were not captured for random villages in random months and is assumed as missing. 53% of the validation model data was not captured and is assumed as missing.

A data point of a village can be classified 'missing' during one data capture event but then 'measured' again at subsequent data capture events. This results in non-monotonic missing data patterns for villages. In this case, the probability of missing values was not related to the value of the observed responses, and thus the data was assumed to be missing completely at random (MCAR) for both the development and validation models (Kang, 2013). In the development model, however, 3% of the data was missing at random (MAR). In this case, the probability of data missing was dependent on the set of observed responses. It is established that an analysis restricted to study participants with complete datasets can be both biased and inefficient (Spratt, et al., 2010) and this is especially a threat to prognostic studies (Vergouw, et al., 2012). However, it has been shown that multiple imputation methods have offered no statistical advantage over complete case analysis in some assessed scenarios (Mukaka, et al., 2016). This study used the complete case analysis for data evaluation. The reduced dataset assumed the removal of the MCAR cases and was shown to still produce valid estimates for statistical modelling as it represents a randomly drawn sub sample dataset of the original dataset (Bennett, 2009).

2.7 Statistical Analysis

Multivariable regression with a backwards selection procedure was used to decide which of the candidate predictor variables should be included in the final prediction model, with a p-value of less than 0.05 ($p < 0.05$) taken as a conservative indicator of inclusion in the dataset.

In backward selection, all the selected covariates are firstly entered at the same time into the model. Subsequently, the variables with the highest p-values are removed based on the Wald test that allows the calculation of the significance level of a predictor. This step is repeated until there are no variables left with a p-value greater than 0.05 (Steyerberg, et al., 2001). After the backward stepwise regression was performed, the following variables: 1) month, 2) latrine built after CLTS, 3) latrine with handwashing and, 4) latrine privacy, remained in the development model. The variables: 1) champion and, 2) SAG meeting, 3) latrine in use, 4) latrine lids and, 5) latrine with smooth and cleanable floor were excluded. The variable 'village population' was added to the model due to a p-value of 0.059, very close p-value to $p < 0.05$ criterion. The ability to include variables outside the criteria of $p < 0.05$ is supported by literature (Hendriksen, et al., 2013).

Prognostic models in general appear to perform better in datasets used to develop the model than in new datasets. In this case, the regression coefficients and the measures of performance for the model are optimistic (Steyerberg, et al., 2004). To correct for the optimism, the study's development model parameter estimates were penalised by a shrinkage factor. To estimate the shrinkage in the model, the study used the Van Howelingen and le Cessie shrinkage estimator (Van Houwelingen, 2001).

In the Van Howelingen and le Cessie shrinkage technique, the regression coefficients are multiplied by the heuristic shrinkage factor and the intercept is re-estimated (Pajouheshnia, et al., 2016). The study's internal validation associated the amount of shrinkage by comparing the model's apparent C-statistic to the C-statistic computed by nonparametric bootstrap resampling. The bootstrap-resampled C-statistic corrects for regression towards the mean and overfitting (Steyerberg, et al., 2001). The internal bootstrap validation C-statistic for the study used the Harrell's nine steps on 200 bootstrap resamples of 688 cases each.

To record overall predictive performance in addition to discrimination, calibration was used. Discrimination is the ability of the risk score to differentiate between villages which do and do not experience an adverse event during the study period (Steyerberg, et al., 2010). This measure is quantified by calculating the area under the receiver operating characteristic (ROC) curve. A value of 0.5 represents chance, 0.7 ≤ ROC <0.8 represents acceptable discrimination, 0.8 ≤ ROC <0.9 represents excellent discrimination, and a value of 1 represents perfect discrimination (Hosmer & Lemeshow, 2000).

Calibration is the ability to accurately assign the correct event probability at all levels of predicted risk (Crowson, et al., 2013). It measures the agreement between the observed and predicted risks. It is computed as the difference between the mean observed risk and the mean predicted risk. To measure calibration, the study used the Hosmer-Lemeshow goodness-of-fit test. In the Hosmer-Lemeshow goodness-of-fit test, model outputs are sorted into equally-sized groups, where the probabilities and true states in these groups are then checked by a x^2 goodness-of-fit test (Dreiseitl & Osl, 2012).

In each group, the expected number of events for ODF status loss in each group of villages was calculated as the sum of the predicted probabilities for the villages in that group. Whereas the observed number of events for ODF status loss was calculated as the sum of the number of events observed in that group (Crowson, et al., 2013).

The study used the December 2016 revised version of Stata/IC 14.2 for windows to all its statistical analyses (StataCorp, 2015). The study followed the Transparent Reporting of a multivariable prediction model for Individual Prognosis or Diagnosis (TRIPOD) statement in its reporting (Collins, et al., 2016).

3 RESULTS AND DISCUSSION

3.1 Study Baseline Data

A total of 803 cases were available for the development model and 676 cases for the validation data set. The villages that did not have any data reported over some

Table 2 Development and validation models key study characteristics

Characteristic	***Development model*: *Chungu chiefdom* (*n* = 688)**	***Validation model*: *Chabula Chiefdom* (*n* = 313)**
Data collection period	October 2016 to September 2017	October 2016 to September 2017
Study design	Retrospective prognostic study	Retrospective prognostic study
Setting	Chief Chungu ODF chiefdom predominately agricultural economy	Chief Chabula ODF Chiefdom predominantly fish farming economy
Inclusion criteria	All villages reported in the DHIS2 WASH MIS with two or more months' worth of data in the system	All villages reported in the DHIS2 with two or more months' worth of data in the system
Outcome	ODF or ODF status loss	ODF or ODF status loss
Total number of villages included in study	67	56
ODF Status	688	313
ODF	618 (89.8%)	246 (78.59%)
ODF status loss	70 (10.2%)	67 (21.41%)

months in the DHIS2 WASH MIS (i.e. 97 cases), were removed. Table 2 provides a summary of key study characteristics. The final development model had five covariates, with an events per candidate (EPV) equal to 14. The validation model had an EPV of greater than 13.

3.2 Internal Validation

The ODF status loss risk model, when internally validated, had a high discrimination (apparent C-statistic = 0.8114, 95% CI = 0.75049 to 0.87240). A Hosmer-Lemeshow of 0.2377 confirmed no significant difference between observed and predicted ODF status loss. The mean for the observed risk seems to be accurately estimated by the mean for the predicted risk grouped by tenths of predicted risk.

3.3 Bootstrap Validation

The difference in the true probabilities from the model's prediction was at 95.9% and the percentage of fit due to noise was 4.12%. This overfitting was estimated by the heuristic shrinkage estimator. After bootstrapping with 200 resamples, the optimism-corrected C-statistic was 0.802. The predicted equation for the ODF status loss model was penalised to account for 1.2% overfitting using the Harrell method (Harrell , et al., 1996) with a heuristic shrinkage factor of 0.988.

3.4 External Validation

The model from the development cohort was penalised for overfitting and applied to an external validation set. The discrimination of the model in the new data set was high (C-statistic=0.844, 95% CI 0.788 to 0.899) and the model was well calibrated with a Hosmer-Lemeshow of p = 0.246 confirming no significant difference between observed and predicted ODF status loss.

The odds ratio of the final model in the prediction equation (Equation 1) indicates that for each one-month increase when other covariates are held constant, the odds of ODF status loss increases by 27.7%, whereas a one person increase in the population for a community with all covariates held constant increases the risk of ODF status loss by 1%. Furthermore, for each latrine that is constructed as a result of a CLTS intervention, the odds of ODF status loss increase by 11.8% when all covariates are held constant. For each handwashing station with soap for a household, the odds of a community experiencing ODF status loss reduce by 20.2% whereas the odds increase by a factor of 4.7 for each increase in a toilet facility that has privacy, all things being equal.

$$P = \frac{1}{1 + e^{-x}} \quad (1)$$

where;

$x = -4.459\ (0.245t + 0.01n + 0.112l - 1.599h + 1.540v)$

P = ODF status loss

t = time (months)

n = village population (people)

l = number of latrines built after CLTS (latrines)

h = latrines with handwashing with soap facility (handwashing facility)

v = latrine privacy (latrine wall and door or suitable acceptable substitutes)

The above example results agree with literature accounts on the influence of variables such as: time after ODF attainment, population growth, CLTS interventions and toilet quality on the sustainability of ODF maintenance for villages. ODF sustainability evaluations have estimated an annual ODF status loss rate of 10% per year; with a five-year status loss rate of up to 50% (Thomas, 2016; Tyndale-Biscoe, et al., 2013). ODF status loss in these cases refer to a return in open defecation.

The provision of technical support (ODF sustainability measures) by local and external support agencies following ODF status attainment has been identified as a significant factor in ODF sustainability (Tyndale-Biscoe, et al., 2013). These ODF sustainability measures are collaborative interactions of streamlined government line agencies, local natural leaders and chiefs (Balfour & Singh, 2015). There is also evidence suggesting that the ODF status of a community can still be sustained despite limited follow-up enforcement following ODF status obtainment (Thomas, 2016).

This study also reinforces the findings from a study in Ghana and Ethiopia on sustainability of CLTS outcomes. The study asserts that CLTS is not an appropriate intervention in cases where the baseline toilet coverage is low and local toilet technologies are poor (Crocker, et al., 2017). Poor quality latrines can cause households to revert back to open defecation (Tyndale-Biscoe, et al., 2013; Mosler, et al., 2018). The CLTS methodology encourages communities to construct low cost, simple toilets that leverage on locally available materials (Mosler, et al., 2018). The implementation of CLTS is premised on the assumption that households will upgrade the initial simple low-cost toilet hardware to increasingly higher standards toilets (Khale & Ashok , 2008). Undeveloped sanitation supply chains and poor sanitation markets coupled by unstable soil conditions however, contribute to ODF status loss (Munkhondia, et al., 2018; Garn, et al., 2017). Poor sanitation markets further exacerbate ODF status loss due to their influence on the access to handwashing products such as soap. A correlation in lack of handwashing with soap and ODF status loss was established at 8% (Shivanarain & Nancy, 2015). A cross sectional study to ascertain the association of ODF status loss and the strength of social norms in Indonesia for 587 households after a two-year ODF period estimated the status loss rate at 14.5% (Odagiri, et al., 2017).

4 STRENGTHS

This study's strength is an exhaustive use of the easily accessible DHIS2 WASH MIS repository data. Furthermore, the external validation of the chiefdom's nomadic fish farming and peri-urban social economic setup in selected parts of communities, were distinct characteristics to that of the development model. The study further aligned its statistical plan and results to the TRIPOD statement to ensure for quality and standards. To ensure for transparency, the study used two vigorous and robust measures to correct the overfitting in the model; the heuristic shrinkage estimator and the Harrell method for bootstrapping. The final model was then subject to correction for optimism.

5 LIMITATIONS

Bias of misrepresentation of data by the community cadres cannot be completely ruled out. Whilst the adverse events satisfied recommendations in literature of EPV of greater than 10, adverse events were small in the validation cohort than what is being advocated for in recent literature of at least a 100 adverse events (Collins, et al., 2016). Furthermore, recent literature has advocated for larger EPV values of between 20 and 50 (Austin & Steyerberg, 2014). Complete case analysis was undertaken in the presence of 3% missing at random (MAR) data. The study had a strict adherence to statistical rigor in the selection of study covariates. The relationship between covariates was not explored in this study.

The results can be considered when applying future interventions and the prioritisation aspects of service provision. However, cultural, geographical, socio-economical and other factors may have a particular impact on particular predicators and should be considered in all applications of these results. Caution should be exercised when interpreting the results in contexts where the ODF definitions differ from those defined in this paper.

6 CONCLUSION AND IMPLICATIONS

The study has developed and externally validated a novel population risk prediction algorithm that can predict a twelve-month ODF status loss risk for communities with multiple risk factors. The study utilised monthly available data collected through the DHIS2 WASH MIS platform. This prognostic tool represents a novel and yet simple approach to assessing the risk of ODF status loss that can be used to inform prioritisation of interventions by the following groups and individuals: sanitation action groups at village level, community champions and government extension officers, district officers, provisional officers and national level and general implementing organisations.

Future research should focus on using prospective data to develop and externally validate the ODF status loss prognostic tool in a larger EPV sample (e.g. EPV >20). Furthermore, a controlled qualitative study should be conducted to ascertain factors that explain the negative influence on ODF status loss post ODF status obtainment due to the following variables village population, quality of toilet infrastructure after CLTS and toilet privacy technologies.

7 OTHER INFORMATION

7.1 Supplementary Information

The web calculator for the risk algorithm model is accessible through the following link.

7.1 Funding

No funding was obtained to undertake the study.

7.1 Ethical Considerations

Ethical approval was not necessary.

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9 APPENDIX

Examples 1 to 5 provide illustrations on the practical interpretation of the prognostic model used the developed calculator. Using the tool, downloadable here, the values in the model are inputted to generate the following results:

$$P = \frac{1}{1+e^{-x}} \tag{1}$$

where;

x = -4.459 $(0.245t + 0.01n + 0.112l - 1.599h + 1.540v)$

P = ODF status loss

t = time (months)

n = village population (people)

l = number of latrines built after CLTS (latrines)

h = latrines with handwashing with soap facility (handwashing facility)

v = latrine privacy (latrine wall and door or suitable acceptable substitutes)

Example 1: *Month following ODF status attainment*

A village within the first month (month = 0) of ODF status and a village population of 105 people (17 households) with 17 latrines built after CLTS, 17 households with handwashing with soap facilities and 17 households with latrines providing privacy, when presented with a risk of ODF status loss, would have the risk of status loss of 7%. Maintaining all prognostic factors constant, an increase in the number of months after ODF attainment to 6 months, increases the risk of ODF status loss to 25%. Whilst an increase to 12 months, the risk of ODF status loss increases to 60%.

Scenario 1	Scenario 2	Scenario 3
t = 0	t = 6	t = 12
n = 105	n = 105	n = 105
l = 17	l = 17	l = 17
h = 17	h = 17	h = 17
v = 17	v = 17	v = 17

Example 2: *Village population*

A village with 5 months ODF status having a village population of 60 people (10 households) with 10 latrines built after CLTS, 10 households with handwashing with soap facilities and 10 households with latrines providing privacy, when presented with a risk of ODF status loss, would have the risk of status loss of 11%. Maintaining all prognostic factors constant, an increase in village population to 120 (20 households), increases the risk of ODF status loss to 18%. Whilst a threefold increase to 180, will increase the ODF status loss to 28%.

Scenario 1	Scenario 2	Scenario 3
t = 5	t = 6	t = 12
n = 60	n = 120	n = 180
l = 10	l = 17	l = 17
h = 10	h = 17	h = 17
v = 10	v = 17	v = 17

Example 3: *Latrines built after a CLTS intervention*

A village with 5 months ODF status having a village population of 105 people (17 households) with 0 latrines built after CLTS, 17 households with handwashing with soap facilities and 17 households with latrines providing privacy, when presented with a risk of ODF status loss, would have the risk of status loss of 4%. Maintaining all prognostic factors constant, an increase in latrines built after a CLTS intervention by half (8 of 17 households), increases the risk of ODF status loss to 9%. When all the 17 households in the village have all their latrines built after a CLTS intervention, the risk of ODF status loss increases to 21%.

Scenario 1	Scenario 2	Scenario 3
$t = 5$	$t = 5$	$t = 5$
$n = 105$	$n = 105$	$n = 105$
$l = 0$	$l = 8$	$l = 17$
$h = 17$	$h = 17$	$h = 17$
$v = 17$	$v = 17$	$v = 17$

Example 4: *Handwashing with soap facilities*

A village with 5 months ODF status having a village population of 105 people (17 households) with 17 latrines built after CLTS, and none of the households with handwashing with soap facilities, whilst all the 17 households are with latrines providing privacy, when presented with a risk of ODF status loss, would have the risk of status loss of 100%. Maintaining all prognostic factors constant, an increase the households with latrines having handwashing with soap facilities by half (8 of 17 households), still maintains the risk of ODF status loss at 100%. When all the 17 households in the village have all their latrines with a handwashing with soap facility, the risk of ODF status loss reduces to 21%.

Scenario 1	Scenario 2	Scenario 3
$t = 5$	$t = 5$	$t = 5$
$n = 105$	$n = 105$	$n = 105$
$l = 17$	$l = 17$	$l = 17$
$h = 0$	$h = 8$	$h = 17$
$v = 17$	$v = 17$	$v = 17$

Example 5: *Latrines providing privacy*

A village with 5 months ODF status having a village population of 105 people (17 households) with 17 latrines built after CLTS, and 17 households with handwashing with soap facilities, whilst all none of the households are with latrines providing privacy, when presented with a risk of ODF status loss, would have the risk of status loss at several multiples of a 100%. Maintaining all prognostic factors constant, an increase the households with latrines providing privacy (8 of 17 households), still maintains the risk of ODF at several multiples of a 100%. When all the 17 households in the village have all their latrines providing privacy, the risk of ODF status loss reduces to 21%.

Scenario 1	Scenario 2	Scenario 3
$t = 5$	$t = 5$	$t = 5$
$n = 105$	$n = 105$	$n = 105$
$l = 17$	$l = 17$	$l = 17$
$h = 17$	$h = 17$	$h = 17$
$v = 0$	$v = 8$	$v = 17$

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