Research Paper

Up-scaling sanitation provision using mixed design methodologies and failure risk assessment: a case study of Marikuppam, India

M. Gormley, L. A. Williams and B. Ongole

ABSTRACT

Simplified sewerage provides an improved alternative to single user on-site options in peri-urban areas in India, and contributes to the aim of reducing the need for human handling of waste (manual scavenging), and the Government's goal of making India open defecation free by 2019. This research develops a mixed methodologies approach to design, optimise and assess failure risk for a proposed installation in a village in India. A steady state simplified sewerage model was used to do the initial design which was further modelled in DRAINET, a numerical model traditionally used for building drainage systems. The input data for DRAINET were obtained from a detailed survey carried out on site, which included usage pattern and focus group data. A total of 106 properties were included in the design and the survey. Test runs were carried out for the whole site over a 12-hour period. All main pipe runs were 100 mm diameter and set to a gradient of 1:100. A risk model was developed and applied to the DRAINET results which confirmed that the design operated effectively; however, there were areas of concern at the extremities of the site, which required additional flow boosting devices or gradient changed.

Key words | design, DRAINET, India, settlements, simplified sewerage

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INTRODUCTION

The UN Sustainable Development Goals (SDG) identify water and sanitation as essential elements to human development. Goal 6 of the UNSDG states the aspiration to 'ensure adequate water and sanitation for all' (United Nations 2015). This paper provides details of an improved approach to sanitation provision that is cost-effective, scalable and sustainable over time: simplified sewerage. A case study site is used to show how, in addition to the steady state designs advocated for simplified sewerage, numerical modelling can provide additional insight into how the whole system might operate post-installation.

Simplified sewerage systems, characterised by shallow gradients provide a real alternative for low to middle income peri-urban places globally (Mara 2005; Bakalian *et al.* 1994). The cost savings can be as much as a third on conventional systems (Nema 2009).

This research is based in India and on the potential for simplified sewerage to provide a major impact on improving sanitation on a massive scale. The inclusion of a risk assessment based on data from the numerical model, DRAINET provides an additional tool with which to advocate the technology.

The mixed methodology approach described in this paper, involving steady state design, comprehensive usage data collection and numerical modelling has ensured that design of a simplified sewerage system is both real and

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relevant. The inclusion of a risk model allows optimisation options to be effectively assessed so that effective decisions can be made at the design stage.

CASE STUDY BACKGROUND

Marikuppam Telugu Line (MTL) is a community of 106 households in Kolar Gold Fields (KGF), Karnataka State, south India (Figure 1) (12° 55′ 4N and 78°15′ 48E). Gold was mined in the area for 2,000 years. Mining is no longer economic and the mines have been abandoned, but many thousands of former mine workers still live in KGF. All of the residents of MTL are from one particular Dalit (untouchable) community. The MTL community was assigned the job of night-soil collection and cesspit cleaning by hand, known as manual scavenging for workers in the gold mines. In traditional Hindu culture, human excreta are considered to be the most 'defiling' of substances. This is the case for those from MTL, the practice being so stigmatised that those who do it keep their occupation hidden, even from their families.

In 1991, a group from Marikuppam established 'Safai Karmachari Andolan' (SKA) (*Sanitation Workers Movement*), now a nation-wide movement, to end the 'dehumanising practice' of manual scavenging. SKA were instrumental in promoting national legislation to outlaw manual scavenging in India (Government of India 1993, 2013).

At the request of SKA, Marikuppam was identified as a pilot community for the design of an appropriate sanitation system which could remove the need for manual scavenging

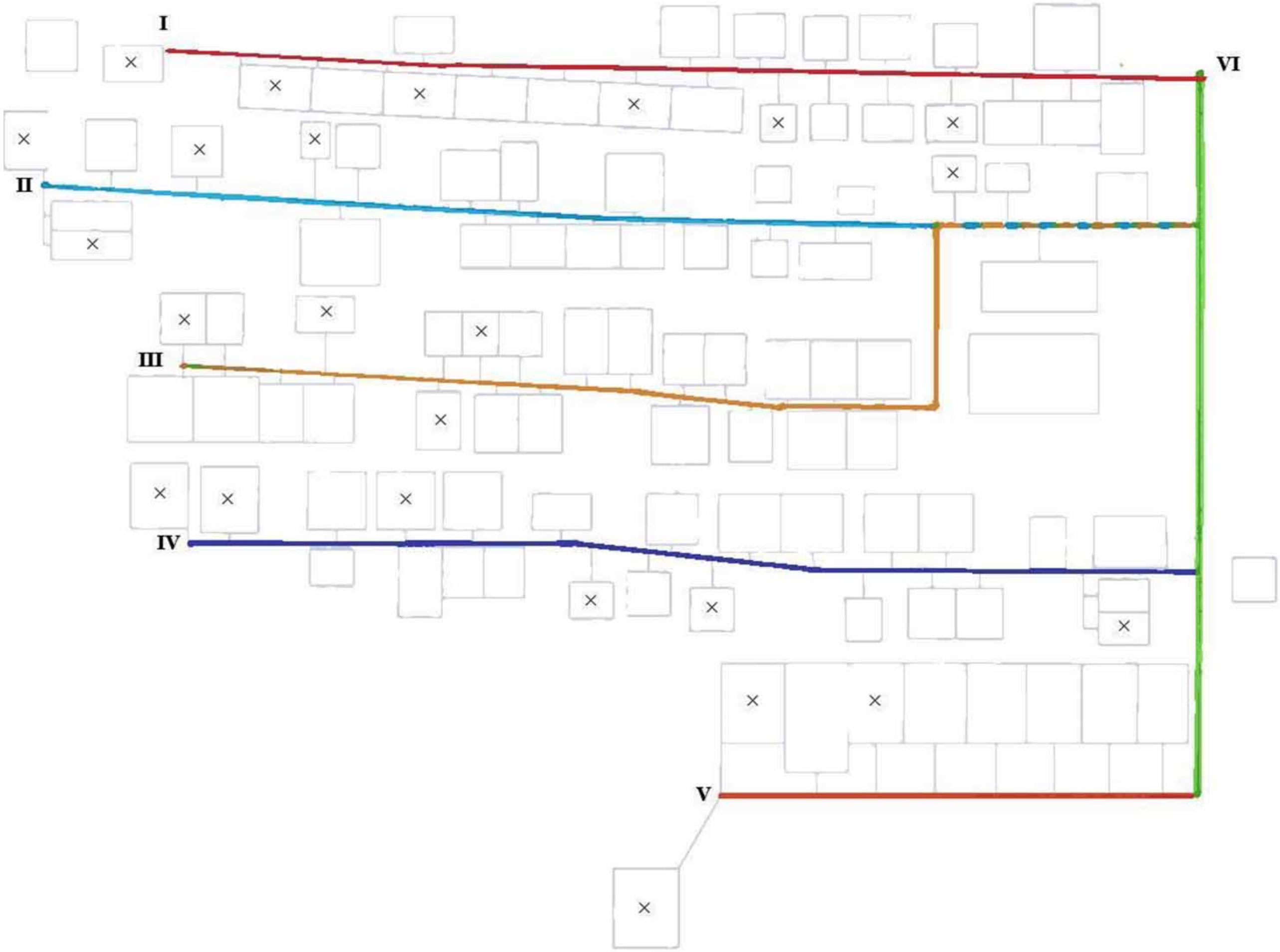

Figure 1 | Site layout showing proposed piped simplified sewerage network.

altogether. Every family in the MTL has been involved with manual scavenging, and 70% of households have no toilet.

A particular concern in MTL is the use of the main available sanitation facilities which are communal toilets located some distance from the houses. Travers *et al.* (2011) found that in Delhi, threats to women and girls' safety using public toilets were exacerbated by poor design, maintenance and lighting in addition to men and boys gathering around the block, a common theme through similar studies (O'Reilly 2010). These issues impact women's general health. To avoid needing to use the toilets during the day, many women and girls restrict their food and drink intake (Bapat 2003). Menstruation is another need which is often not catered for in public toilets (Kulkarni *et al.* 2015), and so managing menstrual periods is a significant source of stress throughout many women's lifetimes (Sahoo *et al.* 2015).

Swachh Bharat (Clean India) is a national programme designed to improve sanitation in India. The programme aims for an open defecation free India by 2nd October 2019, the 150th anniversary of the birth of Mahatma Gandhi. The sanitation programme has already increased the number of households with access to toilets by 20% and is set to continue apace. The majority of the toilets being constructed are of the dry pit latrine type, which in all likelihood will require the services of manual scavengers to empty.

This work focuses on the transportation system for waste and not the processing aspects of the design which would include the construction of a settling tank and constructed wetlands as an appropriate way to deal with the waste.

METHODOLOGY

The general methodology is given below:

- Produce an approximate map of the area from satellite imagery
  - Verification of layout on site
- Local data collection
  - Water usage survey
  - Household survey
  - Focus group discussions
- Determining pipe diameters and gradients
  - Using the PC-based software to calculate the optimum gradient and diameter
- Full system simulation over 12-hour period
  - DRAINET modelling and results collation
- Risk assessment
  - Using the collated DRAINET results in the risk model to assess performance and highlight areas of concern.

The steady state design tool employed an open access programme developed by Mara *et al.* (2001). The water usage survey data from the 106 households was facilited by SKA. The survey included interviews, observation and semi-formal focus groups. The numerical modelling of the entire site was carried out using a modified version of DRAINET (Gormley *et al.* 2013). A risk assessment methodology was developed to enumerate the optimization.

Water usage survey

The survey focused on the following:

- Water availability
- Water usage patterns and consumption
- Number of people per household
- Diet
- Urination and defecation patterns
- Methods of anal cleansing.

The data generated weres used to determine the input water discharge profiles for the DRAINET model.

Household survey

A survey was carried out to establish the number of occupants in each household, split by gender and age. The entire population of 106 households was surveyed. Additional data were collected concerning the occupation of householders, the highest level of education attained, whether they had an electricity connection and their sanitation facilities. This information was primarily used to set the distribution of people within the site and to provide some context for the lifestyle of people in the village.

Water usage

Nineteen households were randomly selected for a survey on water usage – 15 is the minimum number recommended by Feuerstein (1986) as a representative sample of 100 households. In all households but one, women were interviewed. House numbers were written on paper and placed in a bag. Fifteen were chosen from the bag. Four additional houses were selected due to their unique characteristics: two had a large number of occupants, one had recently been upgraded, and one had people with specific needs due to disabilities. Patterns of water use were established by asking occupants the time of day that they would perform each activity. The day was divided into 3-hour blocks to aid with the collection and reporting of the data.

Focus group discussions

Focus group discussions were also conducted to gain qualitative data about the general state of sanitation and health. Participants were asked about diet, sanitation practices, any health problems, menstrual hygiene and the disposal of infant excreta. Additional information was gathered through general comments which participants made.

Steady state design

The design followed Mara *et al.*'s (2001) steady state system approach. The design tool suggested that using 100 mm diameter pipe set at a slope of 1:100 (the natural gradient in most of the site) would be sufficient to ensure drain self-cleansing.

Numerical modelling

In order to assess the risk of blockages occurring in the proposed system, the modelling software DRAINET was used, which was based on a flow velocity model developed at Heriot-Watt University (Swaffield *et al.* 2015) and modified for ultra-low water usage by Gormley (Gormley *et al.* 2013). DRAINET uses the method of characteristics to model unsteady free surface flows by solving Saint Venant equations – a method first applied to small diameter pipes by Swaffield & Galowin (1992).

The characteristics of the solid test pieces simulated were developed in the USA by the Nation Bureau of Standards in the 1980s (Swaffield & Galowin 1992). Typically, solids are 38 mm in diameter and 75 mm in length with a range of specific gravity from 0.85 characteristic of a vegetarian diet with water as the main method for anal cleaning, to 1.2 (characteristic of a heavy meat diet with other matter used for anal cleaning). Extensive validation has shown that these solids act in a similar way to real solids in a drainline. Solids begin as discrete faeces and will break up as they travel. When these solids reach their natural maximum transport distances then an amalgamation can occur, to form larger solids again (Gormley & Campbell 2006; Swaffield *et al.* 2015). The criterion for success is the evaluation of solid deposition distance and progress through the entire system over a specified period of time.

House type profiles

Gormley & Dickenson (2008) detail a methodology for modelling large, complex systems using DRAINET. House types are characterised and usage scenarios are modelled separately, then connected to represent the entire system. A similar process has been followed to develop the methodology for modelling this system.

Characterisation of house types

The village consists of a wide range of household sizes – from one single occupant to a family of 17. House types were characterised based on the water use data available and the number of households of each size in the population. These were:

- House type A: 1 or 2 occupants
- House type B: 3 occupants
- House type C: 4, 5 or 6 occupants
- House type D: 7, 8 or 9 occupants
- House type E: 10 to 17 occupants.

Water usage – patterns

A DRAINET simulation can be run for a maximum of 43,200 seconds, or 12 hours. To account for this, the times used in the model were limited to between 7:00 and 19:00, with water usage outside these times being ignored – the data collected showed that the majority of water usage occurred within these 12 hours.

Within each house type, the most common 3-hour window for each activity was found. A random number generator was then used to determine in which minute of the 3-hour window each of the water discharges would occur. This distributed the discharges randomly across the 3-hour window for a given house type and avoided simultaneous discharges.

Creating individual device profiles

Using DRAINET, discharge profiles were then created for each type of water use. The profile for a 2-litre pour-flush was based on findings by Lehmann (2014). This pour-flush characteristic was confirmed by the focus group discussions.

Creating 12-hour house discharge profiles

Individual device discharge profiles were added together to create each of the different 12-hour profiles. A simulation was then run for 43,200 seconds (12 hours) to allow for consistency in the time intervals for each.

Variations for each house type were also created. House types A and B did not generally undertake tasks such as laundry and household cleaning every day. For these, two profiles were created, one with the task and one without. For other house types, offset profiles were created to simulate households waking and eating at different times.

Simulating discharges from rows of houses

A simulation of wastewater flows in each row of the network was run separately. Houses at the end of rows and those with longer distances to the main pipe were selected as potential locations of problems. Solids were introduced to the system at these points so that solid transport could be assessed.

Risk assessment

In order to assess the impact of different changes made to the system in decreasing the chances of blockages occurring, a method was developed to calculate a coefficient which could be compared across different configurations. For the purposes of this assessment, the risk of blockage occurring was divided into three levels:

- Primary risk – the risk of at least one solid causing a blockage;
- Secondary risk – the risk of half of all solids causing a blockage;
- Tertiary risk – the risk that every solid would cause a blockage.

Calculating the risk of solids causing a blockage

In assessing these risk levels it was necessary to make an estimate for the risk of blockage – dividing the time taken for each solid to reach the end by the total observation period, 12 hours. This assigns a value between 0 and 1 to each solid, with higher numbers representing a higher risk of blockage.

Primary risk calculation

The following equation shows a generalized method for calculating the likelihood of a blockage occurring in any row:

$$P_{row} = 1 - \left[\left(\prod_{i=1}^{n} \left(1 - \frac{t_i l}{2 d_i t_o} \right) \right) \cdot \left(1 - \frac{\sum_{j=1}^{n} (t_j l / 2 d_j t_o)}{n} \right)^{m-n} \right]$$

where n is the number of solids modelled; m is the highest number of solids modelled in any row; t is the time taken to reach the end of the pipe; t_o is the observed time period; l is the total length of the row; d is the distance the solid has travelled; P_{row} is the likelihood of a blockage occurring in the chosen row.

The risk of the whole system failing – that is, at least one solid failing – can then be quantified using:

$$P_{system} = 1 - \left[\prod_{i=1}^{n} (1 - P_{rowi}) \right]$$

where P_{system} is the likelihood of a blockage occurring in the system; P_{row} is the likelihood of a blockage occurring in each row; n is the number of rows. Note that failure in this context means that a major blockage could occur, as a direct result of the design itself, and therefore needs to be evaluated.

Secondary risk calculation

The secondary risk is calculated to represent three of the total six solids in each row causing a blockage, using the following equation:

$$P_{row} = \frac{n!}{0.5n!^2} \cdot \left(\frac{\sum_{j=1}^{n} (t_j l / 2 d_j t_o)}{n} \right)^{0.5n} \cdot \left(1 - \frac{\sum_{j=1}^{n} (t_j l / 2 d_j t_o)}{n} \right)^{0.5n}$$

where n is the number of solids modelled; t is the time taken to reach the end of the pipe; t_o is the observed time period; l is the total length of the row; d is the distance the solid has travelled; P_{row} is the likelihood of a blockage occurring in the chosen row.

The likelihood of half of all solids in the system reaching the end of their respective pipes can then be calculated as the mean probability of the rows in the system:

$$P_{system} = \frac{\sum P_{row}}{n}$$

where P_{system} is the likelihood of a blockage occurring in the system; P_{row} is the likelihood of a blockage occurring in each row; n is the number of rows.

Tertiary risk calculation

The tertiary risk is calculated as the risk that the entire system will block – that is, that none of the solids modelled reach the end of the pipe within the 12-hour period. It can be calculated as follows:

$$P_{row} = \prod_{i=1}^{n} \left(\frac{t_i l}{2 d_i t_o} \right)$$

where n is the number of solids modelled; t is the time taken to reach the end of the pipe; t_o is the observed time period; l is the total length of the row; d is the distance the solid has travelled; P_{row} is the likelihood of every solid causing a blockage in the chosen row.

The figure for the whole system is then calculated in the same fashion to find the likelihood of every solid causing a blockage:

$$P_{system} = \prod_{j=1}^{n} P_{rowj}$$

where P_{system} is the likelihood of a blockage occurring in the system; P_{row} is the likelihood of a blockage occurring in each row; n is the number of rows.

RESULTS

Demographics

A total of 558 people live in households of sizes ranging between one person and 17 people. The most common household sizes were those with four, five or six occupants, as shown in Figure 2.

Water supply

Clean water in the area comes from three main sources. The public supply is piped from a borehole. This is available three times a week for an hour and a half, if power is available – power cuts in the state of Karnataka are frequent (Sharma 2015). Households are charged Rs 20 per month for access to this supply, and are permitted to fill six 18-litre pots at each opening. There is also a private tanker which supplies water from the borehole, at Rs 2.5 per 18-litre pot. Bottled water is available from private suppliers for Rs 10 per 20-litre container, which some households drink in preference to water from the borehole.

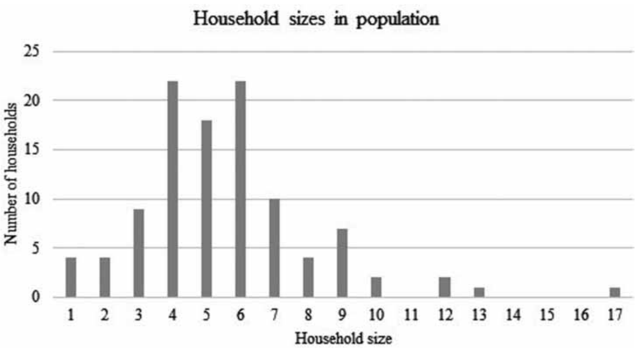

Figure 2 | Distribution of household size in the study population.

The average water usage per person determined from the water use survey is approximately 50 litres per day per person. However, this figure varied greatly from household to household, with figures from 10 to 97 litres per day per person reported.

Water use

Eight main water uses were reported:

- drinking
- cooking and food preparation
- washing vessels and utensils
- bathing
- household cleaning
- laundry
- latrine use
- domestic animals.

Overall, the largest single use of water for each house was laundry, with larger households generally washing clothes every day and smaller households washing clothes between one and four times a week. Bathing also used a large quantity of water, with most adults using between one and two 18-litre pots daily.

The return factor – the percentage of total water consumption which ends up in the sewer system – is typically assumed to be 80% or 85% (Mara *et al.* 2001). However, in some households in this area, the return rate is clearly much lower than this, particularly since laundry water is often discarded elsewhere.

Water use hydrographs

The water usage and water usage patterns obtained from the surveys were converted into hydrographs (Figure 3(a) and 3(b)) to be input into the model to assess the ability of the system to transport solids. Water usage hydrographs are presented in Figure 4 relating to the layout shown in Figure 1.

Numerical modelling results

Figure 4 shows graphically the results for solid transport for one row, Row I. The flow profile for the row is also shown for completeness. The dotted lines indicate the travel of solids over the period of simulation. For this row, the maximum length is 140 m so all solids have clearly passed on to the collection drain.

DISCUSSION

In general, the modelling confirms that the usage patterns obtained from the survey are adequate to keep solids moving through the network and the system operating effectively.

An important point clearly demonstrated by these results is that discharges other than toilet flushes play a significant part in solid transport. This means that in order for the system to function effectively, wastewater from other household activities must be deposited into the system. This could be achieved by either depositing wastewater into the latrine, or by having a secondary drain in the bathroom for wastewater, which people may prefer.

Assessment approach

Generally, the risk of failure was calculated for the original design as carried out in the steady state software and modelled in DRAINET. Optimisation efforts focused on assessing changing pipe gradient, pipe diameter and introducing a flow boosting device (tipping tank) and calculating the risk coefficient as a result. In two cases the discharge events were doubled to assess the impact of surge distribution on solid transport.

Individual rows

The results for each row show that some rows are significantly more problematic than others. Generally, the introduction of a tipping tank or changing the gradient has a positive impact upon reducing the risk of blockage. The best method differs between rows: for rows I, III, IV and V the gradient change made the largest difference, whereas for row II the tipping tank makes more of a difference. Figure 5 shows the primary risk for all rows with a range of options.

Discussion of risk assessment

The equations used to calculate coefficients of risk provide a figure for comparison, but in order for the method to

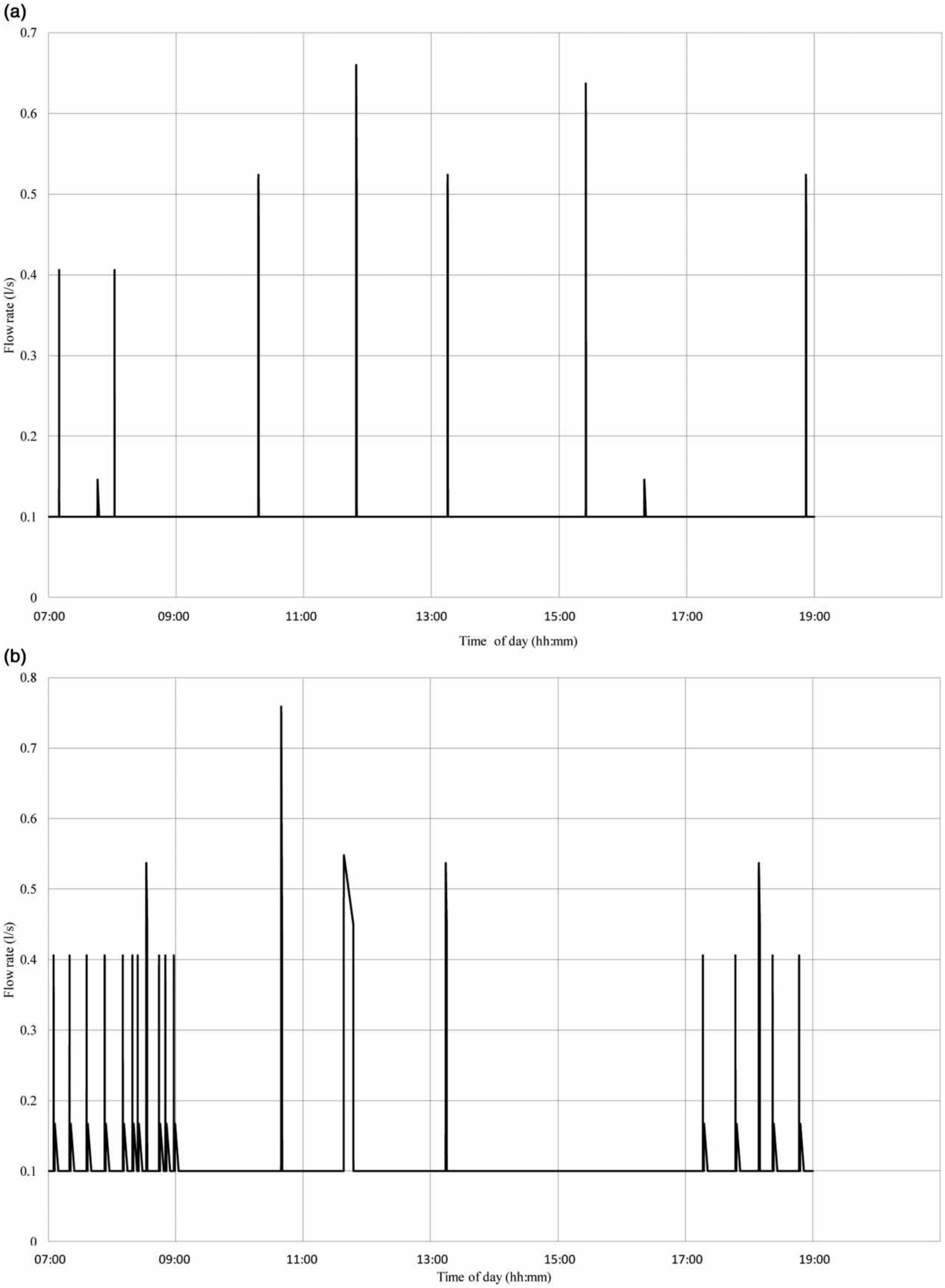

Figure 3 | Water use hydrographs for two house types: (a) house type B and (b) house type D, showing the distribution of discharges into the drain across the 12-hour period.

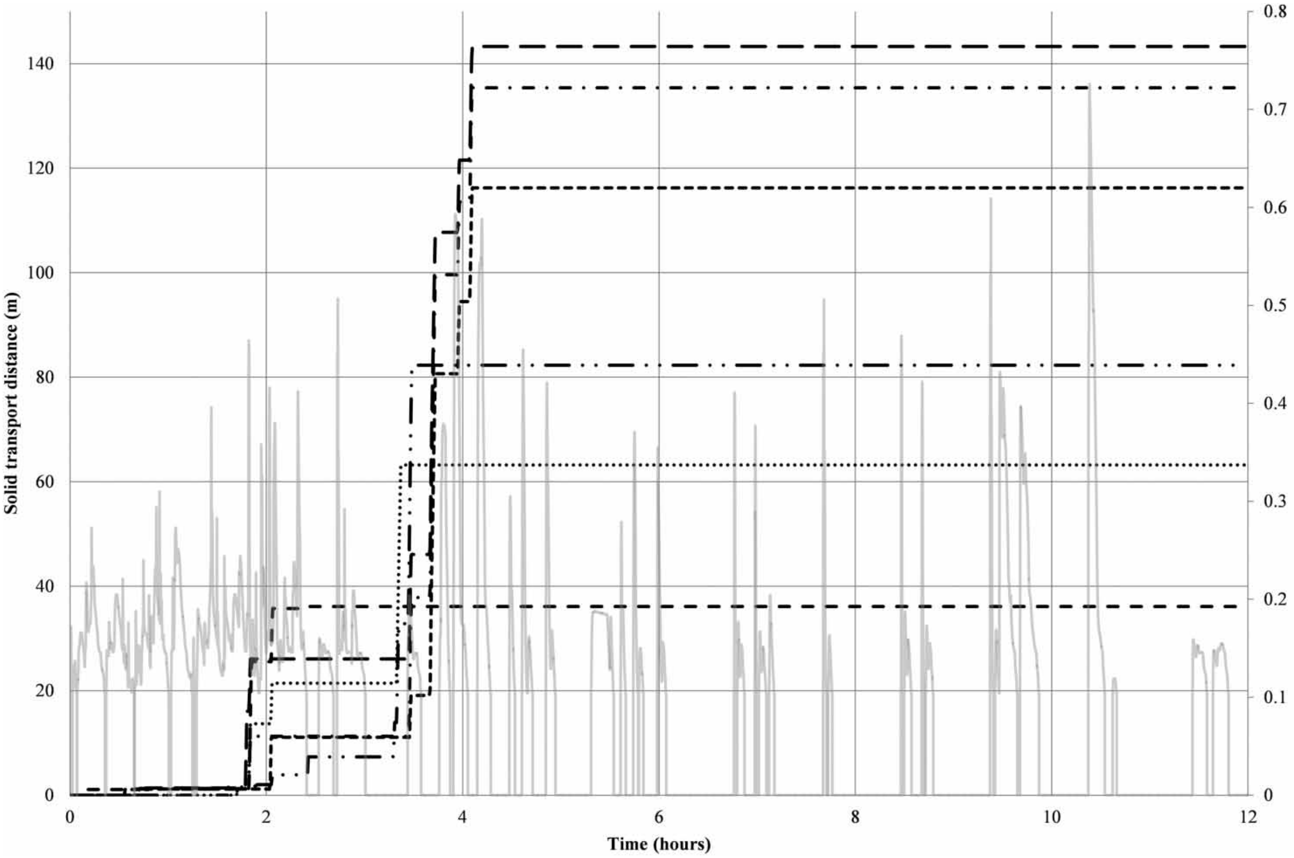

Figure 4 | Results for Row I showing solid transport and water discharge hydrograph (dotted lines show progress of solid trough system).

assist with decision-making these values must be translated into a scale by which the acceptability of the risk can be measured. For the purposes of this assessment, a primary risk value of 0.6 or under was classed as a low risk, values between 0.6 and 0.8 were classed as medium risk and values above 0.8 were classed as high risk (see Table 1).

It can be seen that in some cases the inclusion of a tipping tank slightly increases the risk of failure (blockage). This may seem counter-intuitive, however it is a phenomenon that can occur depending on the location of the tipping tank in relation to the solid mass. The characteristics of a tipping tank are that it produces a large surge wave by dumping a volume of water into the drain in a short time period. This can cause the water to wash over the solid without moving it, or moving it in a random fashion. The result of this is that occasionally a surge from a tipping tank makes little or no difference and can disrupt the solid's transport trajectory in a negative way. The advantage of using the risk assessment in this case is that it highlights these issues and they can be assessed without having to install the system first.

This is also true for the changes in gradient. The original gradient was set to 1:100 (which also happened to be close to the natural gradient of the site) and improvements were seen by increasing the gradient to 1:80. Again, this shows how easy it is to see the improvement. The risk assessment adds a quantity to the decision-making process in relation to the design.

CONCLUSIONS

The research developed a method for evaluating a simplified sewerage design appropriate for installation in a case study village in India.

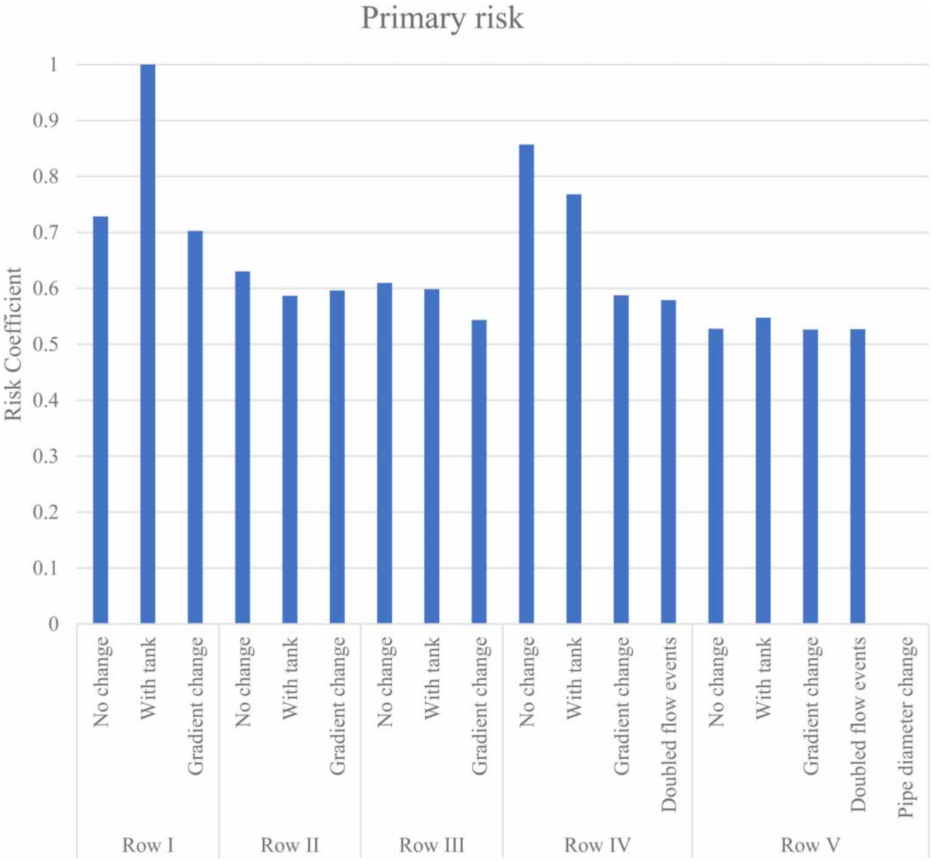

Figure 5 | Primary risk levels for individual rows showing risk level for proposed improvements.

Table 1 | Risk levels for individual rows with different configuration options

		Risk of failure
Row I	No change	Medium
	With tank	High
	Gradient change	Medium
Row II	No change	Medium
	With tank	Low
	Gradient change	Low
Row III	No change	Medium
	With tank	Low
	Gradient change	Low
Row IV	No change	High
	With tank	Medium
	Gradient change	Low
Row V	No change	Low
	With tank	Low
	Gradient change	Low

A water use survey, focus group discussions and household survey provided context information and driver data for the model. An average water use of 50 litres per person per day was determined together with usage patterns. An initial design using a steady state design tool suggested 100 mm diameter pipes set to a slope of 1:100 would be sufficient. This design was then modelled in DRAINET and solid transport results analysed.

Overall, the system performed well – all of the modelled solids reached the main pipe by the end of the 12-hour period confirming that a simplified sewerage system would work; however, results indicated that properties at the extremities of the site performed less well.

A risk assessment tool was developed to enumerate the risk of blockages in different parts of the system, leading to a robust optimisation approach during the design phase.

Improvement options included flow boosting devices (tipping tanks), change of pipe gradient and change of pipe diameter. The risk model was simplified to provide a traffic light (low, medium, high risk) indicator of risk.

This design case study of Marikuppam was requested by a local grass roots organisation concerned with the eradication of manual scavenging. The results presented suggest that simplified sewerage is a feasible, sustainable low cost sanitation option that eliminates the need for human handling of faeces at the individual house level.

REFERENCES

Bakalian, A., Wright, A., Otis, R. & de Azevedo Netto, J. 1994 *Simplified Sewerage: Design*. Guidance, 7(34). UNDP-World Bank Water and Sanitation Program, Washington, DC.

Bapat, M. 2003 Our needs, our priorities; women and men from the slums in Mumbai and Pune talk about their needs for water and sanitation. *Environment and Urbanization* **15** (2), 71–86.

Feuerstein, M. T. 1986 *Partners in Evaluation. Evaluating Development and Community Programmes with Participants.* Macmillan, London.

Gormley, M. & Campbell, D. P. 2006 The transport of discrete solids in above ground near horizontal drainage pipes: a wave speed dependent model. *Building and Environment* **41** (4), 534–547.

Gormley, M. & Dickenson, S. K. 2008 Implications of grey water re-use on solid transport in building drainage systems. In *CIB W62 International Symposium on Water Supply and Drainage for Buildings*, Hong Kong. Available at http://www.irbnet.de/daten/iconda/CIB11915.pdf.

Gormley, M., Mara, D. D., Jean, N. & McDougall, I. 2013 Pro-poor sewerage: solids modelling for design optimisation. *Municipal Engineer* **166** (ME1), 24–34.

Government of India 1993 *The Employment of Manual Scavengers and Construction of Dry Latrines (Prohibition) Act, 1993.* Ministry of Housing and Urban Poverty Alleviation (MHUPA), New Delhi, India.

Government of India 2013 *The Prohibition of Employment as Manual Scavengers and Their Rehabilitation Act, 2013.* Ministry of Housing and Urban Poverty Alleviation (MHUPA), New Delhi, India.

Kulkarni, S., O'Reilly, K. & Bhat, S. 2015 Sanitation vulnerabilities: women's stresses and struggles for violence-free sanitation, Sanitation and Women in India. In: *SHARE and WSSCC Research Findings Conference*. November 7–8, Delhi, India.

Lehmann, H. A. 2014 *An Appraisal of the Use of Intermittent Discharge Devices in Refugee Camp Sanitation. Honours Dissertation Thesis*, Heriot-Watt University, Edinburgh, UK.

Mara, D. D. 2005 Sanitation for all in periurban areas? Only if we use simplified sewerage. *Water Science and Technology – Water Supply* **5** (6), 57–65.

Mara, D. D., Sleigh, P. A. & Tayler, K. 2001 *PC-Based Simplified Sewer Design.* School of Civil Engineering, University of Leeds, Leeds.

Nema, A. 2009 *Simplified Sewerage – An Appropriate Option for Rapid Sanitation Coverage in Urban Areas*. Report Foundation for Greentech Environmental Systems, New Delhi, India.

O'Reilly, K. 2010 Combining sanitation and women's participation in water supply: an example from Rajasthan. *Development in Practice* **20** (1), 45–56.

Sahoo, K. C., Hulland, K. R. S., Caruso, B. A., Swain, R., Freeman, M. C., Panigrahi, P. & Dreibelbis, R. 2015 Sanitation-related psychosocial stress: A grounded theory study of women across the life-course in Odisha, India. *Social Science and Medicine* **139**, 80–89.

Sharma, M. 2015 *Why Bengaluru's Power Cuts are the Worst in 25 Years, NDTV*. http://www.ndtv.com/bangalore-news/why-bengalurus-power-cuts-are-the-worst-in-25-years-1216347 (accessed August 2, 2017).

Swaffield, J. A. & Galowin, L. S. 1992 *The Engineered Design of Building Drainage Systems.* Ashgate, Aldershot, UK.

Swaffield, J., Gormley, M., Wright, G. & McDougall, I. 2015 *Transient Free Surface Flows in Building Drainage Systems.* Routledge, Abingdon, UK.

Travers, K., Khosla, P. & Dhar, S. 2011 *Gender and Essential Services in Low-Income Communities.* Report Women in Cities International, Montréal, Québec, Canada.

United Nations 2015 *Sustainable Development Goal 6*. https://sustainabledevelopment.un.org/sdg6 (accessed August 2, 2017).

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