Water point failure in sub-Saharan Africa: the value of a systems thinking approach

ELISABETH S. LIDDLE and RICHARD FENNER

Thousands of water points have been installed across sub-Saharan Africa over the past four decades; however, a number have been found to be dry/low-yielding, unsafe for human consumption, and in some cases marked with appearance, taste, and odour problems. Subsequently, many users have been unable or unwilling to use these water points and have had to revert to the use of unimproved water sources. A number of factors could be causing each of these problems, either directly or indirectly. Furthermore, these factors may be interdependent and these relationships may be marked by non-linearities, feedbacks, and time delays. Deciphering which factors need to be prioritized becomes a confusing and complex task. To help understand the impact of different interventions, this paper proposes the adoption of systems-based analysis for looking at water point failure and introduces some of the more common qualitative and quantitative analytical tools that could be used to reveal how these complexities might be managed more effectively. While the use of these tools within the WASH sector has been limited to date, they hold potential for helping to identify the most suitable remedies for water point failure. Examples of where such tools have been used in relation to water point failure are reviewed, and the extent to which each approach could be applied is examined from a practitioner perspective, recognizing the limitations arising from the differing data needs and time-consuming nature of each type of analysis.

Keywords: sub-Saharan Africa, rural water supply, systems thinking, systems-based analysis

ACCESS TO SAFE AND ADEQUATE quantities of water is a vital component in alleviating global poverty. Benefits include improved health, increased food security, a broadening of economic opportunities, and an increase in productive/educational hours, especially for women and girls (Hunter et al., 2010; Hutton et al., 2007). For rural sub-Saharan Africa (SSA), access has typically depended on groundwater sources via the construction of shallow, hand-dug wells or handpump-equipped boreholes. While by the end of 2015 SSA had not met the Millennium Development Goal (MDG) for water, advances had been made: 56 per cent of rural SSA had access to an improved source of drinking water compared with

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only 34 per cent in 1990 (WHO and UNICEF, 2015). One piece of abstraction technology has dominated this increase – the handpump-equipped borehole (referred to as *water points* hereafter). By 2015, an estimated 184 million people relied on these across SSA (MacArthur, 2015). However, simply installing a water point and reporting that access has been gained is not sufficient; the water point must function to a satisfactory level over time. According to the Human Right to Water and the WHO/UNICEF Joint Monitoring Programme for Water Supply and Sanitation (JMP), an improved source must provide water that is of sufficient quantity to meet all household needs, safe for human consumption, acceptable from the users' point of view, and physically and economically accessible for all (see OHCHR, 2010; Langford, 2005; OHCHR, 2003).

Table 1 shows that a number of water points across SSA have been reported as failing to meet these improved source standards, particularly those relating to the quantity, safety for human consumption, and acceptability of supply. These supply-based problems have meant that many users have been unable or unwilling to use the water point installed for them; for example, when their water point has been dry or when the taste of the water has made its use unpleasant (Gleitsmann et al., 2007; Katsi et al., 2007; Haysom, 2006; Engel et al., 2005). Furthermore, many of the people who received water points under the MDGs have reverted to the use of often unsafe, unimproved water sources (Gleitsmann et al., 2007). If water point installation is to truly provide increased access, such water points must be actively used.

Identifying the most appropriate remedies for limiting the likelihood of supply-based problems requires an understanding of the factors that are leading to these problems, and the interrelationships between them. Such factors have been reported in the literature with a breadth of publications identifying the causal factors that lead to supply-based problems (for example, Bonsor et al., 2015; Fisher et al., 2015; Walters and Javernick-Will, 2015; Adank et al., 2014; Foster, 2013; Komives et al., 2008; Haysom, 2006; Harvey, 2004; Lockwood et al., 2003; Sara and Katz, 1998). This literature identifies a multitude of natural, technical, social, cultural, and financial factors affecting the quantity, safety, and acceptability of borehole-derived water supplies. While these findings have increased our awareness of the causal factors behind the problems noted in Table 1, knowing which of these hold the greatest leverage for decreasing the likelihood of these problems arising in the future, and subsequently, what interventions need to be prioritized, becomes a difficult and complex decision. While multivariate regression analyses, used for example by Fisher et al. (2015), Foster (2013), Komives et al. (2008), and Sara and Katz (1998), have proven helpful in highlighting the strength of the relationship between a series of causal factors and the state of water point supply, multivariate regression is limited in its ability to include *all causal factors* and *all aspects of water point supply* in a single analysis, especially when the critical variables are not independent, may be internally correlated, and may be qualitative in nature (Walters and Chinowsky, 2016).

When looking at complex problems, there is an essential need to understand, and account for, the entire system of direct and underlying causal factors known to affect the problem that needs to be solved (Maani, 2013). This underlying

Table 1 Some of the data indicating water point supply-based problems across SSA (handpump-equipped boreholes only). These statistics do not reflect national averages (see far right column).

Study	*Water supply problem*	*Proportion of failed water points*	*Country*	*Coverage*
Foster (2013)	Dry	18.2%	Liberia	Nationwide
		17.9%	Sierra Leone	
		19.1%	Uganda	
Anscombe (2011)	Dry	7.0%	Malawi	5 districts
	Sediments in water*	3.0%		
	Poor taste*	3.0%		
	Low yield*	12.0%		
Gleitsmann et al. (2007)	Low yield*	22.0%	Mali	3 communities
Hoko (2008)	Poor taste*	5.0%	Zimbabwe	1 district
Hoko and Hertle (2006)	Dry	17.25%	Zimbabwe	4 districts
	Poor taste*	8.25%		
Harvey (2004)	Yield < 10 ml/min + unable to meet national water quality standards	13.0%	Ghana	5 districts
Whittington et al. (2008)	Dry	10.0%	Ghana	9 districts
Fisher et al. (2015)	Dry	21.6%	Ghana	1 region
Engel et al. (2005)	Sediments in water*	2.0%	Ghana	1 region
	Poor colour*	4.0%		
	Poor smell*	3.0%		
	Poor taste*	7.0%		
	Health concerns*	1.0%		
Hoko (2005)	Poor taste*	17.0%	Zimbabwe	4 districts
	Poor colour*	9.7%		
Hoko et al. (2009)	Dry	38.0%	Zimbabwe	4 districts
Bey et al. (2014)	Seasonally dry	50.0%	Uganda	8 districts
	Poor colour, sediments, and/or worms in water*	42.3%		
	Poor taste = salty*	8.6%		
	Poor smell*	5.1%		
Sangodoyin (1991)	Unsafe supply (Mn)	90.0%	Nigeria	1 state
	Unsafe supply (Fe)	65.0%		
	Unsafe supply (Zn)	10.0%		
	Unsafe supply (Ca)	5.0%		
Adank et al. (2014)	Dry	19.0%	Ghana	3 districts
	Yield < 20 lpcd	39.0%		

Note: * statistic based on users' perceptions.

Dry typically refers to a water point being broken down/not working. Whether this is due to mechanical failure or aquifer/hydrogeology-based failure is not indicated in most studies.

complexity arises from a series of interdependencies, non-linearities, feedbacks, and time delays between the systemic factors, all of which culminate in defining the system structure (Sterman, 2000). When the full system structure is not recognized during analysis, whether this be qualitatively or quantitatively, the ability to find the most powerful intervention points/solutions is greatly limited (Maani, 2013). Based on this need to account for systemic complexity, this paper argues for: 1) the adoption of a *systems thinking mindset* when thinking about the factors that affect the state of water point supply (and how different actors within the sector affect the state of each of these factors); and 2) the consideration of *systems-based analytical tools* when looking for meaningful intervention points for limiting water point supply-based problems.

A systems thinking mindset

A systems thinking mindset is one that seeks to identify and understand the multitude of factors at play when attempting to solve a problem, and their interdependencies. Taking this approach encourages moving away from linear problem solving (i.e. seeing a problem, rushing to an obvious or familiar solution, and expecting the problem to be solved with no consideration of feedback to the initial problem) and instead incites thinking in terms of the holistic web of factors that lie behind the problem at hand (Battle, 2016; Maani, 2013). Once this web of factors is understood, actors can begin to comprehend how their decision, actions, and resource allocations affect different parts of the system.

For example, consider that a water point is installed and a tariff for use is set; yet, because this requires users to pay for use, households continue to draw freely from unimproved sources. A narrow approach to solving this problem would be to look and say: if the tariff is removed, water point use will surely increase. However, as is often the case under a narrow cause and effect approach, through increasing use, a new problem of water point wear and tear is created and eventually the water point will break down. Without funds for repair (tariff removed), users will then be forced to revert to the use of unimproved sources (Figure 1). Through removing the tariff, we recreate the problem we are trying to solve – limited water point use – because of a critical feedback loop. A better option would be to go one layer deeper into the system and address ‘why’ users are unwilling to pay the tariff. Intervening at this level, for example through raising awareness around the need for safe water and the value of paying for safe water, would mean the tariffs could stay in place, use and payment would increase, and cash would be on hand for repairs when wear and tear breakdown occurred. Taking this a step further, and continuing to think at a systems level by asking ‘why’ and ‘what is that factor dependent on’, it would be realised that cash for repair (via payment of tariffs) is only a small part of the repair process. The additional complexities around repair need to be accounted for, including the sourcing of spare parts locally, the quality of these spare parts, access to adequately trained mechanics, and the multitude of actors whose decisions, actions, and resource allocations affect each of these aspects.

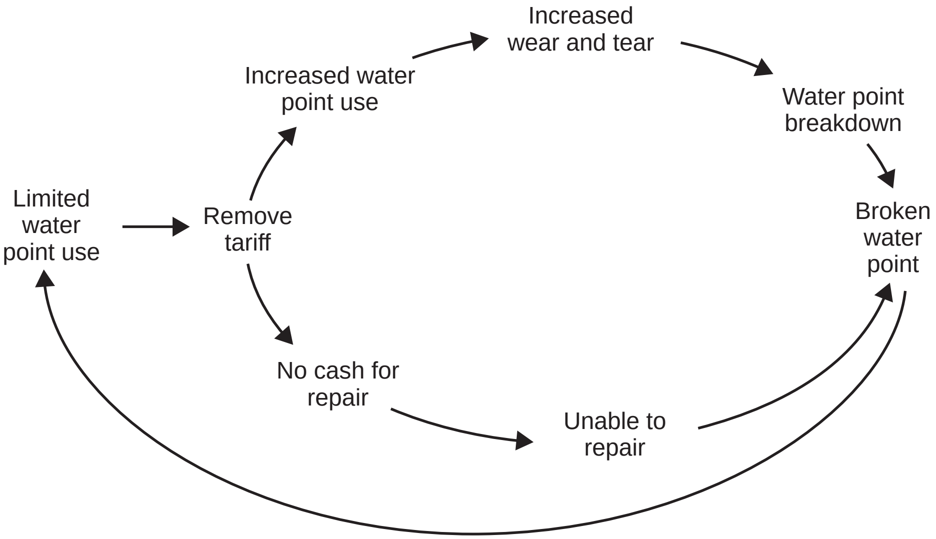

Figure 1 Example of a single solution (remove tariff) for lack of water point use
Source: Authors (2016)

While the situation in Figure 1 is a simplified example, it helps to illustrate that often the solution to a problem is deeper than initially thought. Furthermore, even where one 'deeper' factor is identified that seems to solve the problem at hand, there will, in most cases, be additional factors that need to be accounted for if the solution is to be effectively implemented in practice. A piecemeal approach that focuses on one small factor without regard for the wider system of factors (and actors that influence the state of each of these factors) is not sufficient (Lockwood, 2016). When these deeper causal factors are not considered, essential parts of the picture are lost, limiting the ability to truly solve the problem under consideration (Maani and Cavana, 2007). It is this holistic view that systems thinking promotes. The extent to which an increasingly diverse set of factors need to be considered will depend on how the system boundary is defined (see Box 1). This should be set to reflect the nature of the questions that are to be asked of the analysis. Several water-, sanitation-, and hygiene- (WASH) focused reports arguing for the need to think in terms of systems have recently been published (for example, Lockwood, 2016; Battle, 2016; USAID, 2014). These focus mostly on the interrelationships between actors who need to work together across the WASH community of stakeholders. Hitherto, there has been less emphasis on studying the feedback of decisions from these actors on the performance and service delivery of the physical assets.

Systems-based analytical tools

A range of qualitative and quantitative tools can be used under a systems-based approach (see Maani, 2013) to account for all the distinct but interrelated factors

Box 1 Note on the system boundary

In any systems-based analysis, a system boundary needs to be defined. Where this boundary is placed is important as the boundary determines:

- the extent to which all aspects of the system are included;
- the types of 'what if' scenario/intervention questions that can be asked;
- the type and extent of data needed to develop the systems model;
- the time taken to do all of this (Sterman, 2000).

When defining the system boundary, it is best to work back from the purpose of the analysis, i.e. to identify at the outset what questions the systems model is required to address.

For example, the issue may be the corrosion of rising mains. If the impact of the type of rising main materials used in different geologies was the focus, the boundary could be placed around the physical variables that relate to material performance (ring #1 in Figure 2). However, if this boundary was used, questions around what affects the choice of materials (for example, contract specifications, local access to specific materials, cost of different materials, corruption issues, etc.) would not be accounted for in the analysis. If these broader factors were to be included, the boundary would need to be extended (ring #2 in Figure 2). Digging deeper, the boundary could then be extended to show the impact of project manager expertise, capacity in-country for supervision, import prices, etc. (ring #3 in Figure 2). However, widening the system boundary also extends the range of quantitative data needed to support the analysis, which may be constrained by practical limitations. Conversely, if the boundary is narrow, restricted, and does not look far enough 'out', the ability to understand the factors at play and therefore to find meaningful intervention points is limited. A fine balance is needed here.

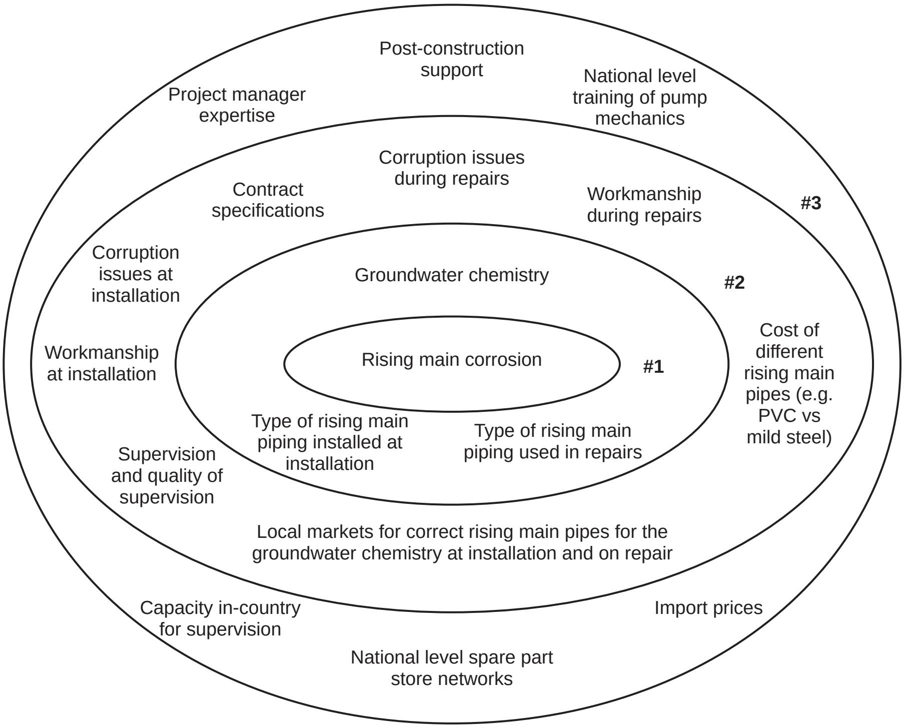

Figure 2 Different system boundaries that could be used when looking at rising main corrosion

that collectively contribute to a problem, on either a qualitative or quantitative basis. This allows: 1) the identification of the hidden complexity and ambiguity behind problems; 2) a qualitative and/or quantitative description of the interdependencies between factors that lie within the system boundary; 3) the ability to observe how the system responds to different solutions/interventions; and 4) the identification of which solution/intervention most effectively remedies the problem at hand.

Qualitative tools are best employed when wanting to gain a 'systemic understanding of problem drivers and barriers and their causal interrelationships' (Maani, 2013: 8) within the system boundary. They help us to develop an understanding of the structure of the system that lies behind a problem (i.e. they help to get the jumbled list of factors and interdependencies onto paper in a structured way). From this, potential interventions can be envisaged (Wolstenholme, 2003). Such descriptive tools map the intuitive perception of a group of participants of a problem and can be used as a stand-alone measure when quantitative modelling is not appropriate for the types of factors that fall within the system being assessed. Qualitative approaches, while having limits to the insights they can reveal, are often adopted where accurate and complete datasets are not available (as is common when looking at problems within rural water supply), where time is limited, or as a precursor to the use of a quantitative tool (Wolstenholme, 1999) to help define the overall system structure by defining key balancing or reinforcing feedbacks.

Quantitative tools use carefully defined relationships to model changes in component parts of the system as information and physical assets flow between them. Having quantified these interdependencies, simulations can be run which allow the prediction of how interventions/changes in one part of the system affect the state of the rest of the system, either as a snapshot or over a period of time (Maani, 2013). Simulation adds significant value as it enables a deeper and more rigorous analysis and has the potential to reveal non-intuitive insights driven by the complex interactions being modelled (Wolstenholme, 1999). This however needs careful calibration and validation against a known performance history of the system and its factors.

The remainder of this paper explains how some of the more common of these tools work and suggests the potential for their use in the WASH sector, with a specific focus on the supply-based problems outlined in Table 1. However, before doing so, a useful summary of systems-based analysis is provided, as explained by Wolstenholme, cited in Maani (2013: 7):

> **What:** A rigorous scientific approach to help thinking, visualising, sharing, and communication of the future evolution of complex systems and issues over time;
>
> **Why:** for the purpose of solving complex multi-stakeholder problems and creating more robust designs, which minimise the likelihood of unpleasant surprises and unintended consequences;

> **How:** by creating conceptual maps [or diagrams] and simulation models which externalise mental models and capture the interrelationships of physical and behavioural processes, organisational boundaries, policies, information feedback and time delays; and by using these architectures to test the holistic outcomes of alternative plans and ideas;
>
> **Within:** a framework which respects and fosters the needs and values of awareness, openness, responsibility and equality of individuals and teams.

Causal loop diagrams (qualitative tool)

Causal loop diagrams (CLDs) are systems-based diagrams that highlight and hypothesize the causal relationships, feedback loops, and time delays that exist between the factors within a given system boundary (Sterman, 2000). Developing a CLD helps to improve the conceptual understanding of the system structure that underpins the problem at hand, and through doing so, enables the identification of the unintended consequences of future interventions (Wolstenholme, 2003).

CLDs are made up of standard symbols. Arrows indicate causal relationships and dependencies between related factors. Quantitative (hard/measurable) and qualitative (soft) factors can be included in CLDs and each factor can be affected by a number of others (Maani and Cavana, 2007). Where a time delay is known to exist within a causal relationship, a || is drawn onto the arrow. The arrows are then marked as positive (+) or negative (–). Positive indicates a reinforcing relationship between two factors: as one factor moves in a certain direction (increases or decreases), the other will follow in the same direction. Negative indicates a balancing relationship between two factors: as one factor moves in a certain direction (increases or decreases), the other will do the opposite (Sterman, 2000). Figure 3a shows a positive relationship: as use of safe water increases, household health increases, or, as use of safe water decreases, household health decreases. Figure 3b shows a negative relationship: as hours collecting water increase, productive hours decrease, or, as hours collecting water decrease, productive hours increase.

Feedback loops are created when a group of causal relationships form a closed circuit. These loops are what cause dynamic behaviours to occur within systems over time (Maani and Cavana, 2007). Feedback loops may be reinforcing or balancing. A feedback loop is called reinforcing (+ve) if it contains an even number of negative causal links, and is considered balancing (–ve) if it contains an odd number of negative causal links. Following this convention can help identify the nature of the underlying system structure. Reinforcing loops lead to self-propelling behaviour

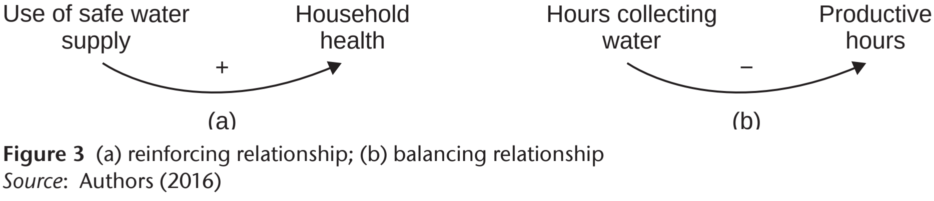

Figure 3 (a) reinforcing relationship; (b) balancing relationship
Source: Authors (2016)

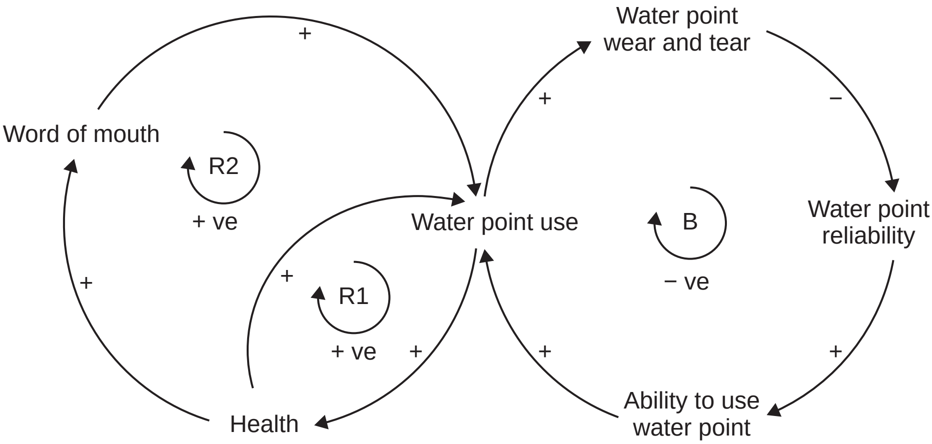

Figure 4 Two reinforcing loops (R1 and R2) and one balancing loop (B) centred on water point use
Source: Authors (2016)

over time (growth or decline), while balancing loops lead to stability/goal-seeking behaviour over time.

Two reinforcing and one balancing loop around 'water point use' are shown in Figure 4. Reinforcing loop 1 (R1) shows the impact of water point use on health; as use increases, health is expected to increase, followed by continued water point use over time. Reinforcing loop 2 (R2) shows how improved health increases word of mouth, and subsequently, water point use by additional community members. Both loops show exponential increase in water point use over time. The balancing loop (B) shows how increased water point use will affect water point reliability; reliability will decrease as use increases. As this loop takes effect, water point use will begin to be balanced/slowed.

Literature reviews and discussions/workshops with experts/stakeholders can be used to develop CLDs. Multiple iterations of a CLD will be needed to get it to a point where it makes logical sense and validly represents the problem at hand. Experts/stakeholders should qualitatively validate the final CLD. CLDs can be digitized using software such as Vensim® (www.vensim.com). The final CLD can be used in a qualitative way for assessing how changes in one part of the system may affect other parts of the system. If the loops involve reinforcing loops, then exponential growth/decline of key factors over time can be expected. However, in the same diagram, there may be related balancing loops that will help in controlling and mitigating this exponential growth/decline over time. If there are no balancing loops, it may be possible to put an intervention in place to create a balancing loop, and so on.

Past CLDs have been used to understand the dynamics of famine (Howe, 2010), conflicts in water sharing (Nandalal and Simonovic, 2003), irrigation in Tunisia (Sušnik et al., 2012), and agricultural soil salinity management (Inam et al., 2015). Box 2 outlines the main CLD advantages/limitations. Sterman (2000) provides step-by-step guidelines for developing CLDs.

Box 2 Advantages and limitations of CLDs

Advantages

- The visual nature of a CLD makes it easy to involve a number of experts/stakeholders in the development process and to explain the system structure to others (Wolstenholme, 1999).
- There is no need for quantitative data (Maani, 2013).
- CLDs stimulate system-wide thinking.

Limitations

- CLDs do not provide quantitative understanding of the impact of each systemic factor on the system as a whole.
- They reflect the insights of those who developed the CLD and the known intuitive dependencies between factors.

Bayesian network analysis (quantitative tool)

Bayesian network (BN) analysis is based on the development of a network that represents a series of factors linked by conditional dependencies and associated probabilities (Sun and Müller, 2013). BNs can be used for quantitative forward (predictive) and backward (diagnostic) scenario testing, as well as for sensitivity analysis, highlighting the factors that have the greatest influence on the area of interest (Cain, 2001).

The first step is to develop a qualitative structure for the BN through literature reviews and discussions/workshops with experts/stakeholders (Düspohl et al., 2012; Cain, 2001), capturing tacit knowledge and understanding from experienced practitioners. In doing so, it is best to begin with the factor of most interest; for example, rising main corrosion in Figure 5. An arrow between two factors, $X \rightarrow Y$, $(\text{cause} \rightarrow \text{effect})$, indicates that the state of Y is conditionally dependent on the state of X (Sun and Müller, 2013). While factors may be represented as either continuous or discrete, most studies discretize any continuous factors into a number of categories as this simplifies the probability calculations involved during scenario analysis. Mutually exclusive states (categories) are then assigned to each factor, which show all possible states a factor may be in (Cain, 2001). In the case of Figure 5, pH, which is a continuous factor by nature, has been discretized into three states; pH at a given water point may be <6.5, 6.5–7.5, or >8.5. As new factors are added, their dependencies to existing network elements are determined.

Figure 5 demonstrates the need to account for all systemic factors when analysing a problem, using rising main corrosion as an example. Initially, the only factors to be included may seem to be the water chemistry of a given site and the rising main materials used at installation (and the associated factors that lie behind non-corrosive rising mains being installed). However, it may become apparent there is a need to look at whether corrosive rising mains are being installed during repair works. If this is a problem, a simple solution would be to ensure that non-corrosive rising mains are available locally. However, there is then a need to look at the cost of these non-corrosive rising mains vs the corrosive options currently being used, and so on, so that in future non-corrosive rising mains are considered.

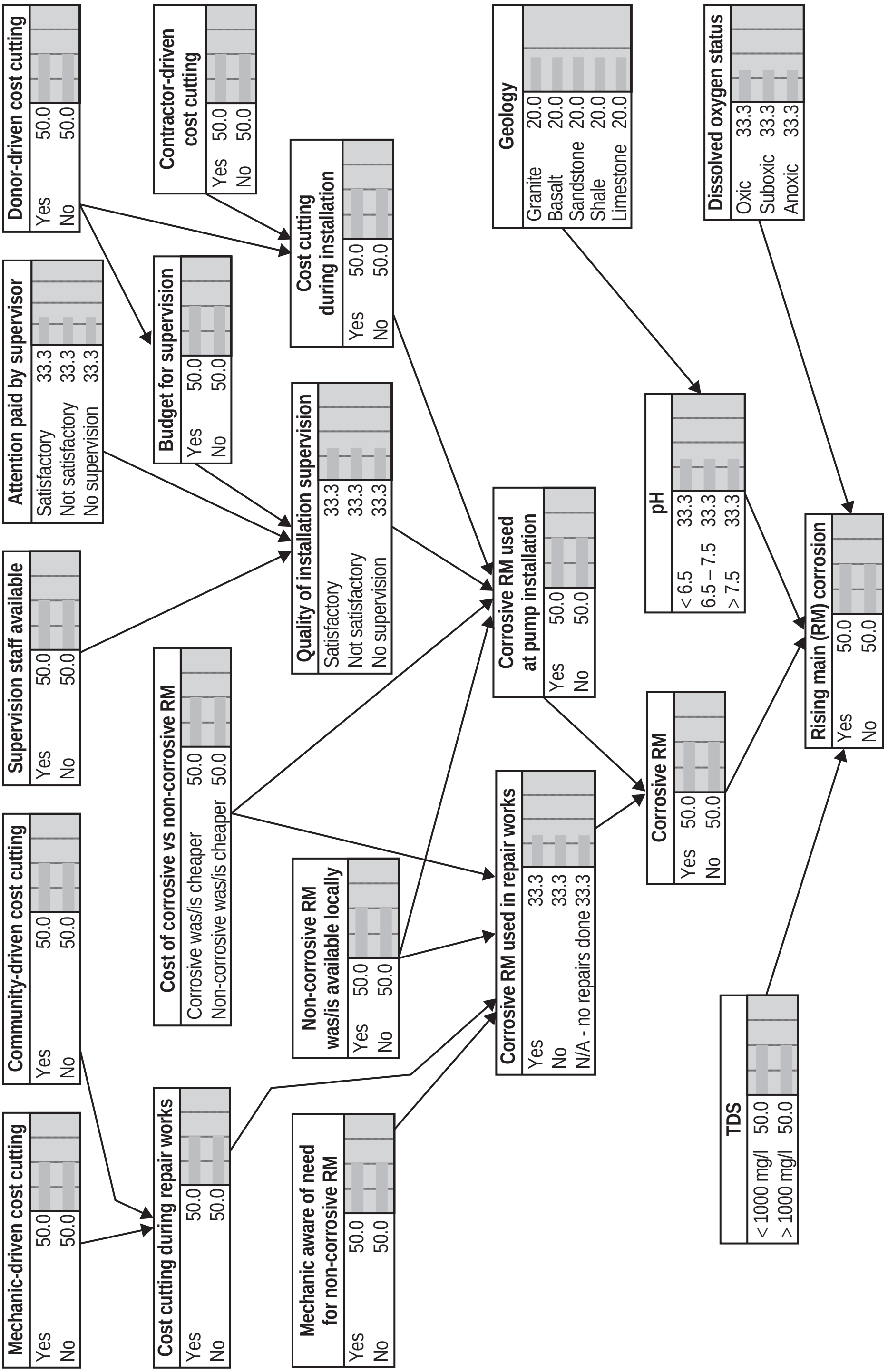

Figure 5 The qualitative structure of a BN centred on rising main (RM) corrosion
Note: the percentages assigned to each factor are initially equally distributed. These would be updated once conditional probabilities are assigned to the network.
Source: Authors (2016)

In the next stage, conditional probability values are assigned to each dependency link based on Bayes theorem (see Sun and Müller, 2013), which states:

$$P(X|Y) = \frac{P(Y|X)P(X)}{P(Y)}$$

Where:

$$P(X) = \text{probability of event } X$$

$$P(Y) = \text{probability of event } Y$$

$$P(X|Y) = \text{probability of observing } X \text{ given } Y \text{ is true}$$

$$P(Y|X) = \text{probability of observing } Y \text{ given } X \text{ is true}$$

These conditional probabilities represent the likelihood of a factor being in a certain state, given all possible combinations of its causal factors. These values can be elicited from direct measurement data, expert/stakeholder opinions, or from previously published models (Cain, 2001). Factors on the edge of the network are assigned prior probabilities (Düspohl et al., 2012). Figure 6 shows a BN centred on water point failure and water point repair among water points in Ghana (Fisher et al., 2015). The percentage bars indicate the likelihood of each factor being in each of its states, given the state of the rest of the system.

Sensitivity analysis can be performed to find the factors that have the greatest influence on the area of interest (which can often be done by using in-built tools within software). Common BN software includes Netica® (www.norsys.com) and Hugin (www.hugin.com). Scenario testing can then be performed. Forward scenario testing allows the identification of interventions that increase the desired outcome the most (for example, repair in Figure 6). Backward scenario testing allows the opposite; the factor of interest's state is set to the desired outcome. The state that all other systemic factors need to be in for this outcome to be achieved will then be calculated by the software. The conditional probability rules behind each factor drive the change in the likely factor states under scenario testing. Sensitivity analysis and scenario testing results are validated with experts/stakeholders by asking if they agree with the sensitivity analysis outcomes and scenario testing results. If direct measurement data was used in defining the conditional probability values, part of this initial data set can be set aside and used for validation.

Fisher et al. (2015) conducted forward scenario testing using the BN shown in Figure 6 to test the impact of certain scenarios on the likelihood of repair (asking, if a water point breaks down, will a repair be likely?). When all management-based factors were set to be in their optimum state (identifiable management present, WASH committee savings >100 Ghana cedis, tariff collected, all necessary tools available, spare parts available within one day, and external support available within one day), the likelihood of repair being yes was 65 per cent compared with 32.7 per cent when these management-based factors were in their worst possible states (Fisher et al., 2015). This supports the notion that there is a need to invest in, and improve,

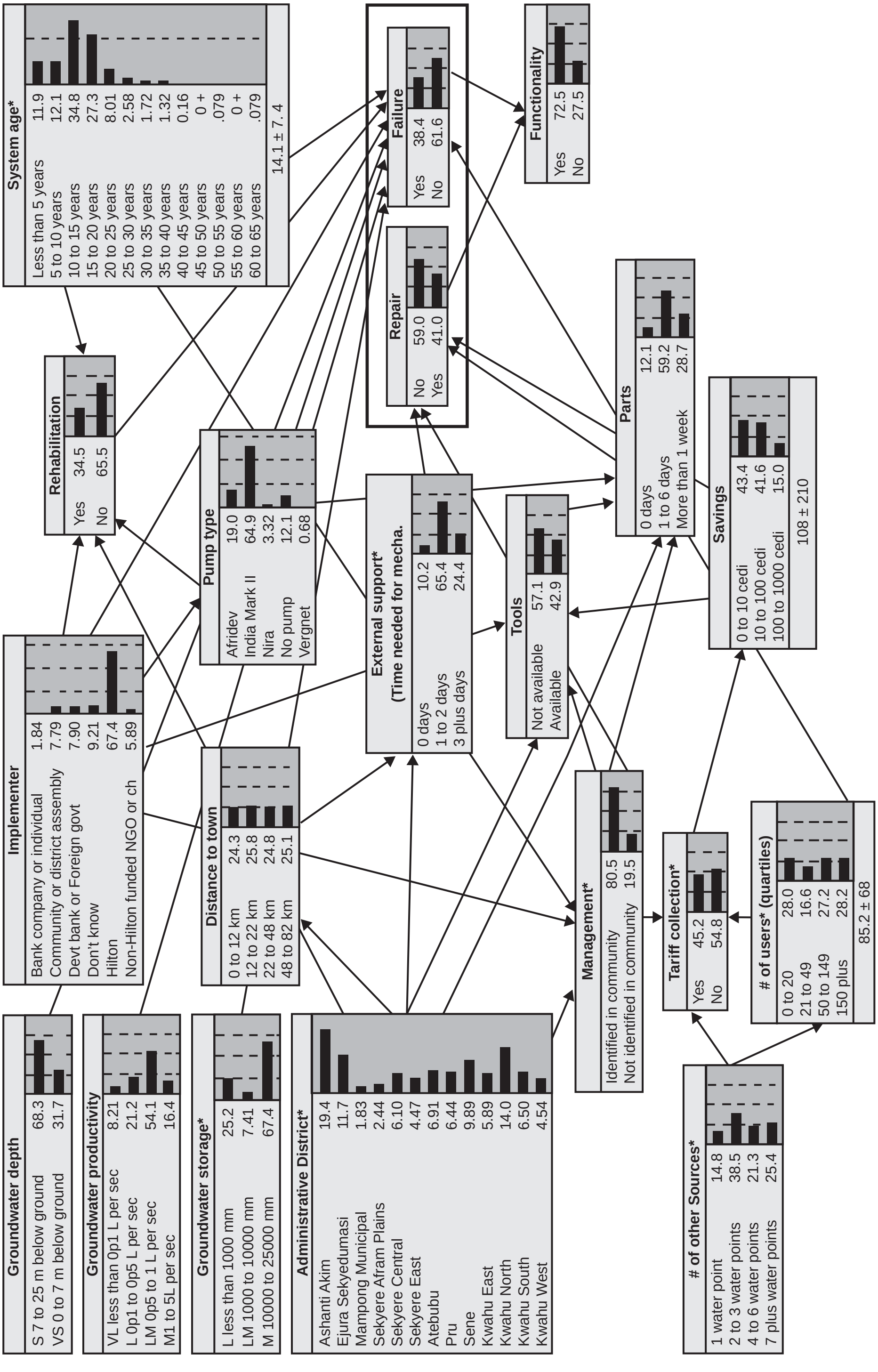

Figure 6 BN showing the likelihood of water point failure and water point repair among water points in Ghana.
Source: Fisher et al. (2015)

management committees, spare part supply chains, and external support structures. A number of other scenario questions could be asked of this model, for example, the likelihood of failure if only the India Mark II pump was installed, or the likelihood of failure if all boreholes were sited in areas that have a groundwater productivity of <0.1 l/s vs the likelihood of failure in areas that have a groundwater productivity of 0.5–1 l/s. These kinds of questions would help to inform future regulations around pump standardization and siting in different hydrogeological areas.

BN analysis has also been used for the probabilistic modelling of pesticide contamination in groundwater sources (Henriksen et al., 2007), water resource demand management (Bromley et al., 2005), native fish abundance (Chan et al., 2012), and quality of agricultural export produce (Banson et al., 2015). In addition to the work conducted by Fisher et al. (2015), BN analysis could be used to assess a number of the water point supply-based problems outlined in Table 1. For example, BN analysis could be used to highlight the relative strength of the different causal factors that lie behind low-yielding water points, and therefore, the factors that need to be prioritized in future drilling projects. Box 3 outlines the main BN advantages/limitations. Cain (2001) provides step-by-step guidelines for developing BNs.

Box 3 Advantages and limitations of BN analysis

Advantages

- The visual nature of a BN makes it easy to involve a number of experts/stakeholders in the development process and to explain the system structure to others (Cain, 2001).
- Subjective factors (those that cannot be ‘measured’ quantitatively in the field) can be included (Cain, 2001).
- Where direct measurement data is not available or where it is not appropriate for the types of factors that have been included, conditional probability values can be based on stakeholder/expert views. In doing so, stakeholder/experts would be asked how many times out of 10 they would expect a factor to be in each of its states, given all possible combinations of states among the factors it is dependent on (Düspohl et al., 2012).
- Qualitative validation of sensitivity and scenario testing results with stakeholder/expert groups is widely accepted. This is useful when direct measurement data are not available (Cain, 2001).
- Uncertainty is dealt with in an explicit way, with results being presented in probabilistic terms (Chan et al., 2012).
- BN analysis allows both forward and backward scenario testing (Cain, 2001).

Limitations

- BNs are snapshots in time. They are unable to incorporate temporal interdependencies and subsequent dynamic behaviours that emerge over time (Ticehurst et al., 2011).
- Poor state selection for each factor may mask the result of scenario testing (Ticehurst et al., 2011).
- Developing the network structure is heavily dependent on stakeholders/experts. Multiple iterations will be needed and this can become very time-consuming. The larger the network, the longer this process will take.
- Eliciting conditional probability values from stakeholders/experts can be a laborious and repetitive task. Balancing stakeholder/expert fatigue with the need for valid data is a challenge.
- BNs can become very complicated and visually messy, with arrows criss-crossing over each other.

Dynamic Bayesian network analysis (quantitative tool)

As with BN analysis, dynamic Bayesian network (DBN) analysis is based on the development of a network that represents a series of conditional dependencies and associated probabilities among the factors within a system boundary. However, instead of representing a single snapshot in time, DBNs operate over a number of discrete time steps. The state of the system at $t = x$ is dependent on the state of the system at $t = x - 1$ (Straub, 2009). The network structure is replicated over x time steps with arrows being drawn between time steps where appropriate (where the state of a factor in $t = x$ is dependent on the state of a factor in $t = x - 1$), assuming the process is Markovian, i.e. predictions of the future system state are dependent on the current system state (Straub, 2009). Additional factors can be added to the network structure in subsequent time steps if needed. As with BN analysis, conditional probability values are assigned to each factor. At each time step, the conditional probabilities of the factors that are dependent on the previous time step are updated to account for this (Cain, 2001). As with BN analysis, DBNs can be validated with experts/stakeholders and/or with direct measurement data if these are available.

The use of DBN has been limited, although it has been used to probabilistically model groundwater pollution (Shihab, 2008), highway traffic movements (Forbes et al., 1995), and the risk of falls among the elderly (Cuaya et al., 2013). For water point supply-based problems, DBNs could be used to assess water point yield throughout the year considering the causal factors that are known to affect yield in each month; therefore, important issues of seasonality can be reflected in the analysis. Guidelines for using DBN are limited; however, Cain (2001) provides a brief overview. The advantages and limitations of DBN analysis are similar to BN analysis in Box 3, with the additional ability to incorporate temporal interdependencies.

Stock-flow modelling (quantitative tool)

Stock-flow models allow us to quantitatively observe how critical elements in a system accumulate or decline over time (Sterman, 2000). A stock can be thought of as some entity that is accumulated over time by inflows and/or depleted by outflows. Stocks can only be changed via flows. Stocks typically have a certain value at each moment of time, and are usually described by a noun. A flow changes a stock over time and is typically described as a verb or rate of change. Underlying these stocks and flows are a series of auxiliary factors, interconnections, feedback loops, and time delays that represent the remainder of the system (Maani and Cavana, 2007). Once fully developed and calibrated, simulations can be run to assess how the system behaves over time and how critical elements quantitatively respond to different scenarios/interventions (Sterman, 2000).

In developing a stock-flow model, the qualitative structure is firstly defined through literature reviews and discussions/workshops with experts/stakeholders. Each systemic factor will be either a stock, a flow, or an auxiliary variable. In drawing the qualitative structure, it is best to start with the stocks and to work out from there. Stocks are represented by rectangles. Inflows are then represented by a pipe (arrow with an hour-glass shape in the middle) pointing into a stock, while pipes

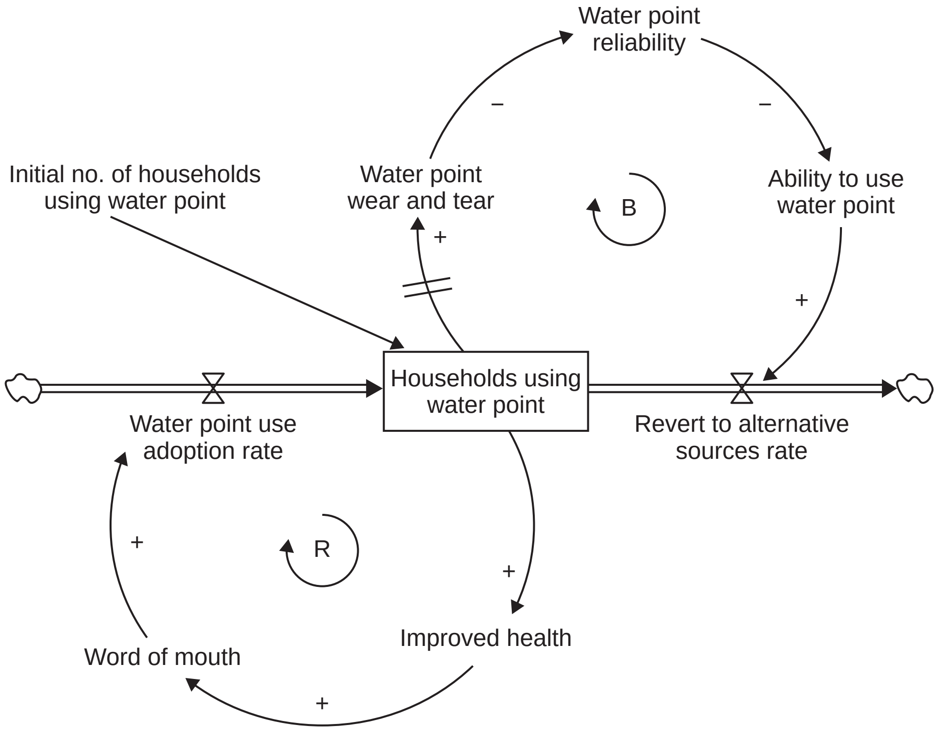

Figure 7 Stock-flow structure for assessing number of households using a water point
Source: Authors (2016)

pointing out of a stock represent outflows. Clouds represent the sources and sinks for the flows where the stock the flow originates from, or the stock the flow feeds in to, is outside the model boundary (Sterman, 2000). An example of a stock-flow model is shown in Figure 7. Here, the stock is the number of 'households using water point', and the flows are 'water point use adoption rate' and 'revert to alternative sources rate'. As with CLDs, positive and negative signs are added to each causal relationship, and feedback loops are allowed and are labelled as reinforcing and balancing.

In quantifying a stock-flow model, mathematical equations are added to each factor. These equations drive the model and indicate the relationship between a given factor and its causal factors. Multipliers can be used and time delays (||) can be accounted for within these equations. Initial values are assigned to each stock, this being its count at $t = 0$ (Sterman 2000). Because stock-flow models predict the future system state, quantitative calibration against historical data is needed (Sterman, 2000). Once the model is able to reproduce the historical system state, simulations of future scenarios can be run. Common stock-flow model software includes Vensim® (www.vensim.com) and Stella® (www.iseesystems.com).

Stock-flow models have been used for understanding demand for municipal water supply (Holmes et al., 2014), developing greenhouse gas mitigation strategies (Han and Hayashi, 2008), understanding the impact of temporary drought pricing on water demand (Sahin et al., 2014), and the impact of subsidy on bio-sand filter use for household water treatment (Figure 8) (Ngai, 2011). Ngai (2011) used this stock-flow model to assess the effectiveness of 18 different NGO resource allocation strategies in increasing the adoption and sustained use of bio-sand filters at the household level, firstly assessing the number of households using the bio-sand filter in 2 years' time under each scenario, and secondly, in 10 years' time. A similar study could be conducted looking at the number of households using a water point daily, the factors that drive the rate of use, and the subsequent impact of use on groundwater levels. Box 4 outlines the main stock-flow modelling advantages/limitations. Sterman (2000) provides detailed step-by-step guidelines for developing stock-flow models.

Agent-based modelling (quantitative tool)

Agent-based modelling (ABM) is a social science modelling tool that allows users to observe: 1) how a group of autonomous agents behave in response to the state of a series of systemic factors; and 2) how these behaviours then, in turn, affect the state of the systemic factors in subsequent time steps (Gilbert, 2007). ABM differs from the other tools reviewed in that, instead of defining the system state via probabilities and differential equations, the system state is defined by the actions of agents

Box 4 Advantages and limitations of stock-flow modelling

Advantages

- The visual nature of a stock-flow model makes it easy to involve a number of experts/stakeholders in the development process and to explain the system structure to others.
- Feedback loops and time delays allow for dynamic system behaviour to be modelled; this makes stock-flow modelling useful when looking for non-linear dynamics within a system (Sterman, 2000).
- Once calibrated, future system state behaviours can be projected with the potential to reveal non-intuitive insights.

Limitations

- Developing the stock-flow model structure is heavily dependent on stakeholders/experts. Multiple iterations will be needed and this can become very time-consuming. The larger the system, the longer this process will take.
- Relationships between factors need to be well defined (based on mathematical equations) if valid model outputs are to result. Being able to define these equations is a difficult task. The extent to which this can be determined will depend on the availability of directly measured data (and whether these data are in the correct form for defining these relationships) and the types of factors that are included. If factors are subjective or based on human behaviour (for example, the impact of word of mouth on water point use adoption rates), this is very challenging.
- Accessing historical direct measurement data for each stock and flow for calibration (Sterman, 2000), especially in the case of rural water supply, can be very difficult.
- As the focus of a stock-flow model is on the changing magnitude within the stocks of the system, stock-flow models are not appropriate when wanting to assess the state factors which do not accumulate or deplete over time.

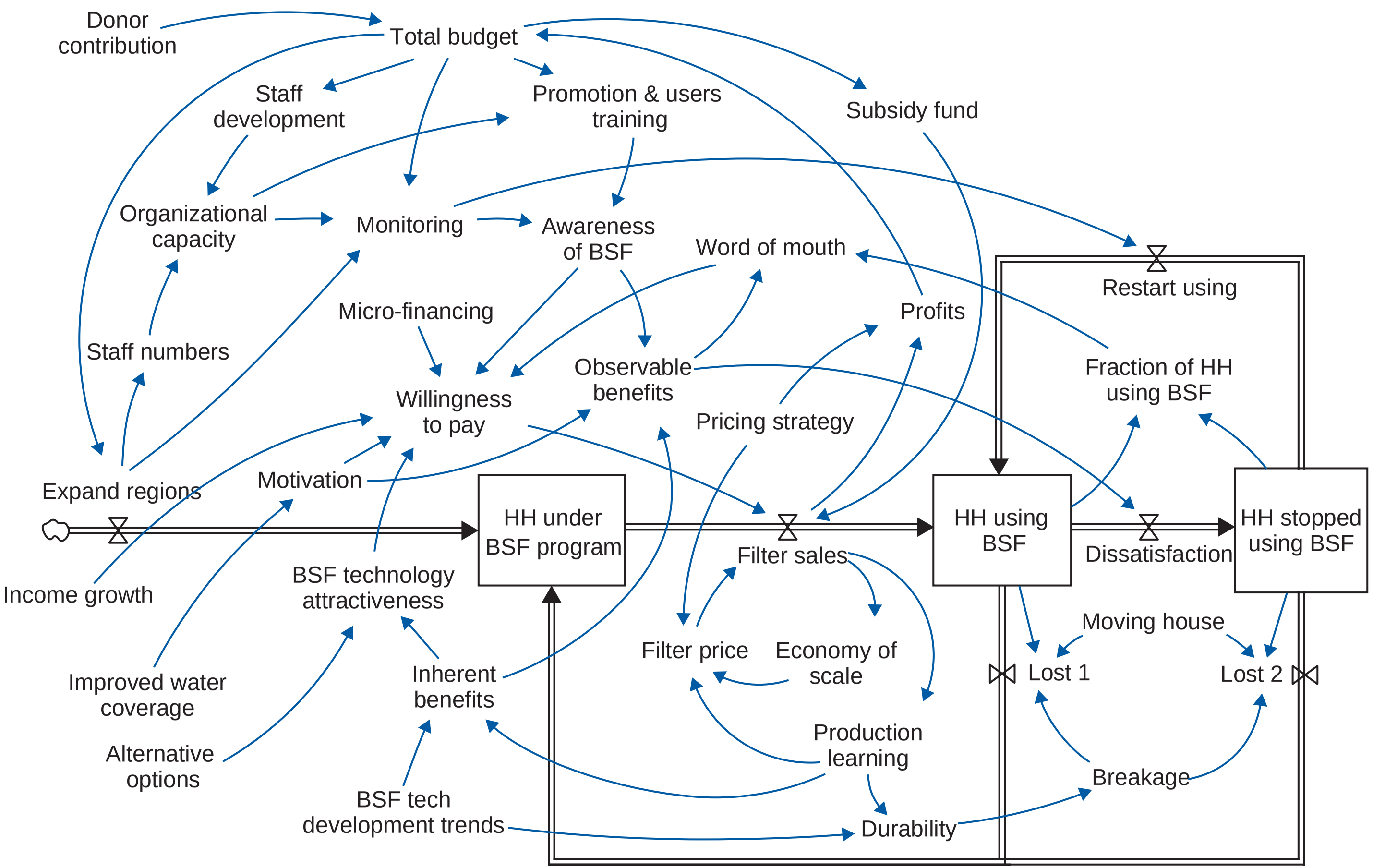

Figure 8 Qualitative stock-flow structure (simplified) for assessing the number of households (HH) using a bio-sand filter (BSF) in India
Source: Ngai (2011)

within the system and their behaviours/decisions at each time step (Gilbert, 2007). ABM allows for the influence of human decision-making on the environment to be incorporated in systems-based analysis and simulation through the coding of behavioural rules.

Agents are social actors, e.g. people, households, firms, organizations, or agencies (Gilbert, 2007). The foundation of an ABM is the environment the agents are embedded within; this may be physical, e.g. a geo-spatial landscape, or non-physical, e.g. a policy environment (Macal and North, 2010). Agents can be connected by alignment in Euclidean space, movement across a cellular grid, between nodes in a network, or movement across physical or political blocks within a GIS system. Behavioural rules are assigned to each agent. These dictate how an agent will act in light of: 1) the environmental factors (systemic factors) that the agent's behaviour is known to depend on; and 2) the behaviour of other agents if appropriate (if *agent x's* behaviour depends on *agent y'*s behaviour) (Gilbert, 2007). Behavioural rules reflect agent tolerance levels/thresholds; hence ABM is useful when assessing social actor tipping points within a system. In addition to these behavioural rules, supplementary properties can be assigned to agents, including the ability to learn/adapt behaviours based on experience, the desire to reach a goal, or by interaction between agents (Macal and North, 2010). Feedback rules are then assigned to the systemic factors; these dictate how the state of these factors will change in response to agent behaviours in each time step (Macal and North, 2010).

Once calibrated, simulations can be run. At each time step, agents will assess the relevant information within their environment, and based on the information they receive, they will decide how to act (Gilbert, 2007). A number of time steps can be simulated with agents repeatedly executing their behaviours. The greater the range of states for each agent, the more varied their behaviours may be. Simulation allows us to observe: 1) how each agent behaves over time (based on their behavioural rules); and 2) how the state of the systemic factors change over time in response to the agents' behaviours. The state of the whole system depends on the aggregated behaviours of all agents (Matthews et al., 2007). NetLogo® (https://ccl.northwestern.edu/netlogo/) is typically used for ABM.

ABM has been used to understand the adoption of new electricity supply technologies among residential and business customers (Hamilton et al., 2009), the adoption of plug-in hybrid vehicles (Pellon et al., 2010), and the complex feedbacks between rancher groundwater pumping rates and environmental conditions in the Rio Sonora Watershed (Pope and Gimblett, 2015). In Pope and Gimblett (2015), agents were individual ranchers, each with their own well and pumping rate. Changes in the depth of groundwater fed back to influence agent behaviour in the next time step, as well as the number of hectares of each vegetation class within the riparian corridor. The model was used to assess the impact of an extended period of drought on groundwater abstraction, riparian vegetation, and the ecosystem services within the riparian corridor. For water point supply-based problems, ABM could be used to model water point abstraction behaviours considering the yield, water quality, and willingness to pay. An agent would be a single household and household behavioural rules may differ based on household income (plus any seasonal fluctuations

Box 5 Advantages and limitations of ABM

Advantages

- The impact of micro-scale behaviours on macro-scale systemic patterns can be assessed (Macal and North, 2010).
- Social interaction and influence between agents can be included (Matthews et al., 2007).
- Heterogeneity/diversity among agents and their behaviours is encouraged, it being this diversity that often leads to dynamic patterns within a system (Twomey and Cadman, 2002).

Disadvantages

- Identifying behavioural rules can be time-consuming, and contentious among social science researchers who question how certain a person/a group of people will act in a particular way given a specified set of conditions. If these rules do not depict reality, the model results will be misleading (Twomey and Cadman, 2002).
- ABM cannot be inverted, i.e. it cannot be set to the desired systemic outcome and then asked to backward predict how the agents need to behave for the desired systemic outcome to result (Twomey and Cadman, 2002).
- Programming skills (most commonly in Java) are needed.
- Model simulations are computationally intensive.

in income), household size, and ability to access alternative water sources (plus any seasonal fluctuations in ability to access alternatives). Box 5 outlines the main ABM advantages and limitations. Macal and North (2010) and Gilbert (2007) provide detailed step-by-step guidelines for developing ABM.

Use of these tools in practice

As the international WASH community continues to strive for universal access to improved water sources, the level of service post-construction must not be neglected and the supply-based problems outlined in Table 1 must be remedied. However, the multitude of factors that affect these problems are diverse and include circumstances associated with the capacity and supervision within the siting and water point construction process, the management and execution of operations and maintenance over time, the collection and management of repair finances, the access to local markets for spare parts and mechanics, and the extent of post-construction support. Furthermore, there are a wide array of actors who play a part within each of these aspects. Thus, identifying policy-based intervention points can become a very confusing and complex task. To identify meaningful intervention points, this system of interrelated factors needs to be understood holistically.

This paper has presented some of the more common tools that have been used for dealing with systemic confusion and complexity, and has referred to how they have been used effectively in other related fields. These tools have the potential to be used in ways that offer interesting and innovative insights as to the most effective remedies for supply-based problems within the rural water sector, as well as in other WASH-related problems. The qualitative methods encourage practitioners to view possible solutions from a valuable systemic perspective encouraging consideration and understanding of the structure of the system when assessing different intervention/policy options. They also have the potential to help different actors within the sector to see how their decisions, actions, and resource allocations affect other parts of the system, and ultimately, the extent to which they help to increase access to improved water sources, not only at installation, but well into the future. The quantitative methods have the ability to then reveal non-intuitive and unintended consequences of proposed actions in a quantitative way.

To date, use of these tools in the WASH sector has been limited. Fisher et al. (2015) (BN analysis) and Ngai (2011) (stock-flow modelling) are examples of studies that have been reported in detail. Perhaps their use has been limited by concerns over their perceived convoluted nature, or because of the seemingly time-consuming and data-intensive processes involved, especially among the quantitative tools. While some approaches do not lend themselves to execution by those directly operating in the field (and are not advocated here for that purpose), their application by others can yield results and important insights that could greatly inform the choices and decisions being made by those practitioners.

As highlighted throughout this paper, an appreciation is needed of the limitations that can be expected of each tool, as well as the different levels of data and technical expertise required to apply each tool to these kinds of problems. Figure 9 provides a summary of the data and technical expertise needed to use each tool, and the computational complexity (or lack thereof for the visual tools) of each. The question now becomes: while it appears that these tools could offer interesting and innovative insights, to what level can each tool truly be used in practice, and furthermore, where should one start?

From a practitioner’s point of view, there is a real benefit to be gained by beginning to use the qualitative aspects of each tool, whether this is through developing CLDs, or the qualitative structures of BNs, DBNs, or stock-flow models (those in the bottom left-hand corner of Figure 9). While much of the clarity and insights that can be achieved through using these tools may already be contained in the tacit knowledge of individual practitioners from experience in the field, employing these tools will help to highlight how the decisions, actions, and resource allocations of different actors start to affect the system as a whole, and ultimately, the access to safe and adequate quantities of water for rural dwellers. Additionally, through developing these qualitative structures, practitioners will be encouraged to ask those ‘why’ and ‘what is this factor dependent on’ questions. Thinking in this way stimulates systems level thinking and helps us to recognize the important wider interdependencies. The more this task is practised, the more normal it becomes to think from this perspective. As explained in Box 1, however, it is important to do so within an appropriate system boundary. If this is set too narrowly and not constantly challenged and reviewed, the ability to find meaningful intervention points will be limited. Once a meaningful intervention point has been identified, the wider impact on the system needs to be examined so that factors which may invalidate or countermand the intervention can be

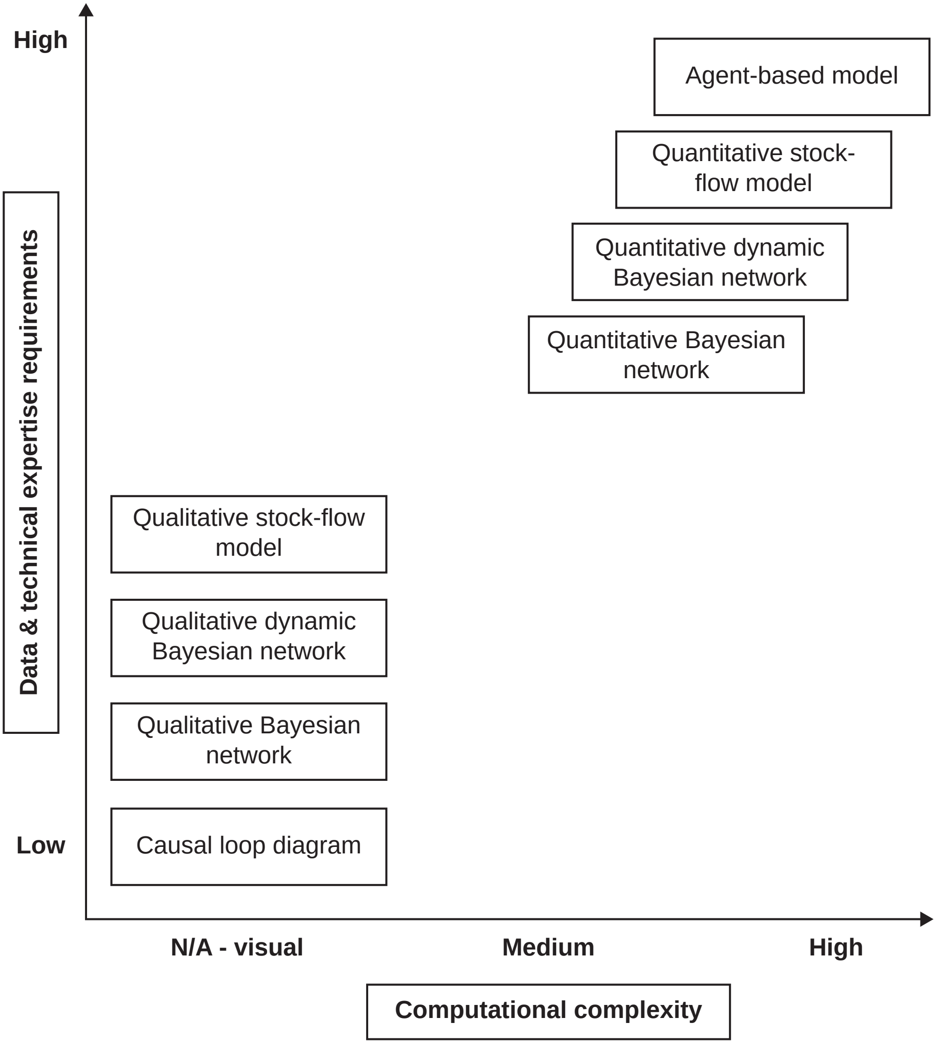

Figure 9 Data and technical expertise required to use each tool as well as the computational complexity that using each involves
Source: Authors (2016)

identified and understood. In terms of using the quantitative tools, given the extensive data and time cost of use, there is an imminent need for research projects and those within academia to test the use of the quantitative aspects of these tools (those in the top right-hand corner of Figure 9) and to build a collection of case studies that firstly demonstrate the benefit to using these tools, and secondly, provide detailed methodological guidelines to help with their adoption among practitioners in the future. There is great potential for these more complex tools to reveal insights that will help inform practitioner decisions and resource allocations in the future.

Conclusion

If the benefits of increased access to improved water sources are to be realized, the supply-based problems that limit use, e.g. dry, unsafe, and unpleasant water, must be remedied. Given the complexities that lie behind these problems, there is a need to move away from narrowly focused problem solving and towards thinking in systems and systems-based analysis when looking for meaningful intervention points. While future research is needed for developing the use of the quantitative tools described in this paper (given their challenges and, in some cases, practical limitations) there are clear benefits in using the qualitative tools described, e.g. through developing CLDs, or the qualitative structures of BNs, DBNs, or stock-flow models. In doing so, and through continually asking the questions of 'why' and 'what is that factor dependent on', practitioners will be able to directly address the holistic web of factors that lie behind the problems they are facing. From this, a better understanding can be achieved of how decisions, actions, and resources allocations within one part of the system will affect the rest of the system.

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