Modes of Failure of South African Local Government in the Water Services Sector

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Abstract:

Water service delivery crises are increasingly prevalent in post-apartheid South Africa. This paper builds on earlier research into the challenges faced by local (municipal) government in the provision of water services, as demand grows and as infrastructure ages. The system dynamics modelling endeavour reported here was undertaken to clarify and explain the on-going socio-technical problems. Six interlinked 'modes of failure' were identified. These include the underinvestment in, and over-extension of, water supply infrastructure; the lack of pro-active infrastructure planning combined with the lack of systematic maintenance; the enforced 'fire-fighting' reaction of municipal staff to service delivery crises; and inadequate financial means, infrastructure capacity, and technical staffing capacity. These modes of failure resonated with the experiences of technical officials from the Sundays River Valley Municipality who had participated in the case study between 2011 and 2015. In addition, the model proved to be an effective tool in communicating the causes of local water services systems failure at national policy level.

Keywords:

mathematical model; service delivery; South Africa; system dynamics modelling; water service provision

Submission summary:

'Modes of Failure' paper (*this document*)

Supplementary material:

'Modes of Failure' model appendices (MS Word doc.):

Supplementary material 1: Vensim model (in '.mdl' format)

Supplementary material 2: SDM-doc report for Vensim model

Supplementary material 3: Sensitivity analysis

DISCLOSURE: An earlier version of this paper was presented at the Second Eskom System Dynamics Conference on the 12th November 2014 in Johannesburg, South Africa. The paper was included in the conference proceedings under the title 'Engaging the challenges of municipal water service delivery using system dynamics'. The conference proceedings are currently in-preparation by Crown Publishers (ISBN 978-0-620-64282-8).

This paper significantly differs to the earlier, working version in the following ways:

1) The model structure has been changed in the 'demand sub-model' and the 'revenue sub-model'; the 'emergency water sub-model' included in the earlier paper (which was supplementary and did not effect model behaviour) has been removed;
2) The description of the model structure (the focus the earlier version) now forms an appendix;
3) Four data variables have been included in the 'demand sub-model' to simulate population growth and housing trends more accurately, therefore changing the model drivers;
4) The causal loop diagram has been updated and refined; lookup graphs for all table functions are included; and supporting data for parameters and initial values are provided;
5) A sensitivity analysis is included as supplementary material; and
6) A discussion on model use, policy relevance, stakeholder engagement and face validation is included.

1. Introduction

In September 2014, violent service delivery protests broke-out in the Sundays River Valley Municipality (SRVM), in which municipal offices and infrastructure were set alight by protestors and burned to the ground. One of the central grievances leading to the protests was that "residents were protesting over water cuts that had lasted for about three weeks" (South African Press Association (SAPA), 2014). The water shortages in this region of the SRVM (Kirkwood) are long-standing (Masondo, 2009; Ndoni, 2009), and have persisted despite extensive interventions from national and regional government departments in South Africa. This paper reports on a system dynamics modelling endeavour, which builds on earlier research in the Kirkwood region into the challenges faced by a small municipality attempting to provide water services in the face of growing demand (Clifford-Holmes, Slinger, Musango, Brent, & Palmer, 2014; D'Hont, Clifford-Holmes, & Slinger, 2013). The research focuses on identifying and explaining the modes of failure in local government water services, seeking to clarify the socio-technical problem. The modelling approach adopted uses methods from the institutional, ethnographic and systems fields, building on understandings derived from stakeholder-engaged modelling with system dynamics (D'Hont, Slinger, & Goessen, 2014; Rouwette & Vennix, 2006; Stave, 2003, 2010; van den Belt, 2004).

The use of system dynamics as a form of quantitative policy analysis is increasing within the international water sector, with its use in investigating the challenges associated with urban water supply expanding in recent years: published applications include focuses on municipal water conservation policies (Ahmad & Prashar, 2010); urban water supply in Singapore (Xi & Poh, 2013) and Korea (Park, Jeon, & Jung, 2013); and urban wastewater management (Rehan, Knight, Unger, & Haas, 2014). By comparison, the application of system dynamics to urban water management in the developing world in general, and Africa in particular, has been limited: the few applications of systems dynamics in the South African water sector – for example – include the relation between a municipality and the physical dynamics of an estuary (Slinger, 1996), and as part of modelling the South African Green economy (Musango, Brent, & Bassi, 2014; UNEP, 2013). This paper, and the associated project that the research is nested within, contributes to filling this gap in system dynamics research.

The structure of this paper is as follows. The case study is first described in order to contextualise the modelling endeavour, following which, the methodology is outlined and the model described. An aggregate causal loop diagram is provided and discussed in the model description section. In section 5, the 'modes of failure' (*MoF*) model is applied to simulating the historical behaviour out of which the September 2014 protests emerged. Finally, the modelling process and model use are discussed, and policy implications drawn.

2. Description of the case study

The Sundays River Valley Municipality (SRVM) is located in the Eastern Cape province of South Africa (see Figure 1). With a combination of multiple small towns and commercial farming, the SRVM is primarily rural, with a number of small urban settlements. The SRVM is the responsible authority for water service provision to all urban water users, in an area of high unemployment and social grant-dependency (around 47% of the SRVM population has a household income of less than $100 per month with unemployment estimated at 44% (SRVM, 2010)). In 2010, several national and regional government departments initiated intervention processes in the SRVM, following an extended period of financial mismanagement and bankruptcy in which the provision of water services in the municipality had suffered. The model described in this paper was developed as part of an action research project that participated in the wider intervention processes in the SRVM. The research was funded by the South Africa Netherlands Research Programme for Alternatives in Development (SANPAD) and was entitled 'From policy to practice: enhancing implementation of water policies for sustainable development' (Palmer, de Wet, Slinger, Linnane, & Rogers, n.d.).

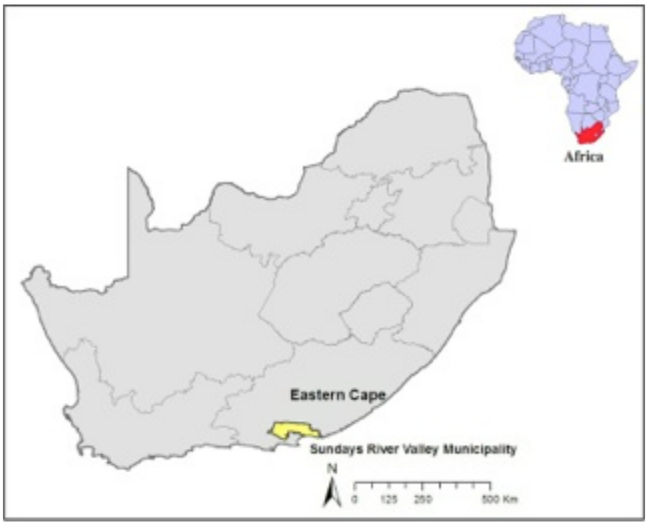

Figure 1: Map of the Sundays River Valley Municipality, shown located within the Eastern Cape province of the Republic of South Africa.

Whilst many of the urban areas in the SRVM face significant water challenges, modelling attention in the SANPAD project has focused on one of the three primary schemes operated by the SRVM, which supplies communities and suburbs of the Greater Kirkwood area. To this end, the 'Greater Kirkwood water supply model' was developed (D'Hont et al., 2013) and then extended (D'Hont, 2013). Early modelling endeavours surfaced a number of issues that were not addressed within the purpose, nor in the design, of the 'Greater Kirkwood water supply model'. These issues included the determinants of the rising demand for potable water in Kirkwood, and the possible alternative sources of water supply that could assist in reducing the severity and frequency of water shortages in the region. These issues were explored in the 'Kirkwood Water Demand Model' (Clifford-Holmes et al., 2014). The foci of these models, and their associated use, did not capture why it was so difficult for the SRVM to either provide adequate water, or to constrain water demand. This paper reports on a modelling endeavour that seeks to explain the continual failures, with a particular interest in the following inter-related dynamics:

- The simultaneous underinvestment in, and over-extension of, water supply infrastructure;
- The effects of municipal staff shortages, emergencies, and over-commitment on standard maintenance activities; and
- The effects of crises and the implications for operations, maintenance and management of municipal water services.

3. Methodology

The challenges of municipal water supply in the SRVM involve multiple interactions of material and informational flows across technical and social systems at different scales. As Forrester (1968, 1970) noted, the manner in which people interact with technical and natural systems is contained in their practices. System dynamics offers an ideal method for exploring these practices and the problems to which they give rise, particularly at the strategic level (Ford, 2009; Sterman, 2000). Given that system dynamics allows for drawing on different kinds of data – mental, written, and numerical (Forrester, 1980) – the method is not constrained by the absence of numerical data sets, which made it appropriate in the SRVM. As found in the previous modelling initiatives (Clifford-Holmes et al., 2014; D'Hont et al., 2013), quantitative data pertaining to water service delivery in the Greater Kirkwood region is limited and subject to a range of uncertainties. Where available, technical reports were consulted in order to provide data for the model parameters and initial states (e.g. Amatola Water, 2014; DWA, 2010; Kwezi V3 Engineers, 2005). A series of workshops and meetings between 2011 and 2014 were then used as additional opportunities for collecting, verifying and validating data (see Table B.1 in the supplementary material). The workshops were attended by representatives from the SRVM and the Department of Water Affairs[1], in addition to impacted and affected stakeholders in the region. These workshops were augmented by fieldwork conducted in the ethnographic tradition of anthropology, which allowed for a rich picture of water services challenges in the SRVM to be developed (Clifford-Holmes, 2015). The site-specific modelling approach employed in this study did not rely on consensus-building, as advocated in group model building (Rouwette & Vennix, 2006), but rather adopted a process of 'methodological hybridisation'(Horlick-Jones & Rosenhead 2007: 588) in the use of institutional, ethnographic, and systems approaches. The novelty of this approach is being argued elsewhere (Clifford-Holmes, Slinger, de Wet, & Palmer, n.d.; Clifford-Holmes, 2015). Interaction with local decision-makers, and impacted and affected stakeholders, on model use and refinement is intrinsic to this approach.

In addition, this case-specific knowledge was used at a more generic level. In a national-level 'Water Dialogue' initiated by the Water Research Commission (WRC) of South Africa, the dynamics captured in the model were used to explain the systemic nature of the modes failure of local government to national policy makers (see Table 1). Modellers collaborated with a senior municipal technical official in presenting the model at the 'Water Dialogue'. This collaboration has extended to co-authoring this paper.

Table 1: Excerpt from the programme of the 'Water Dialogue' hosted by the Water Research Commission in Johannesburg, South Africa on 13/11/2014.

PROGRAMME		
10:00 – 11:00	**Registration** and coffee	
11:00 – 11:15	**Welcome** and introductions	Mr Dhesigen Naidoo, CEO, Water Research Commission of the Republic of South Africa
11:55 – 12:55	**Narratives of hope**: What is this journey "towards a new paradigm" of IWRM practice?	Professor Tally Palmer
	Kirkwood burning: happy oranges and unhappy people in the Sundays River Valley. How can this be hopeful?	Jai Clifford Holmes and partners from the Sundays River Valley
	The Makana Municipality: from provincial administration to empowerment.	Nick Hamer and Partners from the Khulumani Support Group: Water for Dignity & Unilever SA

[1] The national authority responsible for overseeing water was called the 'Department of Water Affairs' (DWA) between 2009 and early 2014, and was renamed to the 'Department of Water and Sanitation' (DWS) in May 2014.

4. Model description

This section describes the *MoF* model in terms of four activities: determining the model boundary; identifying the causal structures driving behaviour; specifying the simulation model; and choosing the settings to simulate the model.

4.1. Determining the model boundary:

An important aspect of system dynamics modelling is setting the model boundary. The variables that are held to be endogenous – i.e. arising from within the system – are central to system dynamics (Richardson, 2011). The endogenous variables in the *MoF* model include the drivers of urban water demand; infrastructure capacity (aggregated across the Kirkwood water supply scheme); the maintenance, refurbishment, and construction of new infrastructure; the activities of technical staff in the municipality and their capacity for work in crisis periods; the effects of over-extending infrastructure above its design capacity; the over-extending of staff capacity over crisis period; and the flows of water-related revenue and expenditure. Exogenous variables include the bulk water loss rate; cost recovery and billing processes and the rates at which staff are hired and leave. The excluded variables include the variable costs of water service provision; the effects of burnout and lack of employee motivation on (and between) municipal staff; and the political exigencies pertaining to recruitment and training processes.

4.2. Identifying causal structures driving modes of failure:

The driver of the system presented in the causal loop diagram (CLD) in Figure 2 is the 'Gap between demand & supply' in the Greater Kirkwood area (in red). This gap *increases* with the 'Total water demand' and *decreases* with 'Water delivered'. The primary driver of water demand in the region is from households that are connected to the municipal reticulation system for drinking water and sanitation services. Historical data suggests that between 2001 (when the municipality was formed) and 2005, 22% of the households in Greater Kirkwood had waterborne sanitation (Kwezi V3 Engineers, 2005). By 2011, the level of service fraction had risen to 77% (Amatola Water, 2014: 3), reflecting that the gap between demand and supply has resulted in 'Pressure on [the] municipality to meet demand' by increasing the 'Connection rate of households'. The more households connected, the more the total 'no. [number] of connected households', which in turn increases the total water demand, and increases the 'gap between demand and supply'. This forms a reinforcing feedback loop (**R1: increasing water demand**).

When there is a gap between demand and supply, the standard response is to adjust the infrastructure capacity, through refurbishment/augmentation of current infrastructure and the construction of new infrastructure. This 'Requirement to increase infrastructure capacity' positively influences the 'New infrastructure constructed', which after a delay, will result in the total 'Infrastructure capacity' increasing, and with it, the 'Potential supply of water', and the water delivered. This is the first balancing loop (**B1: Infrastructure construction loop**).

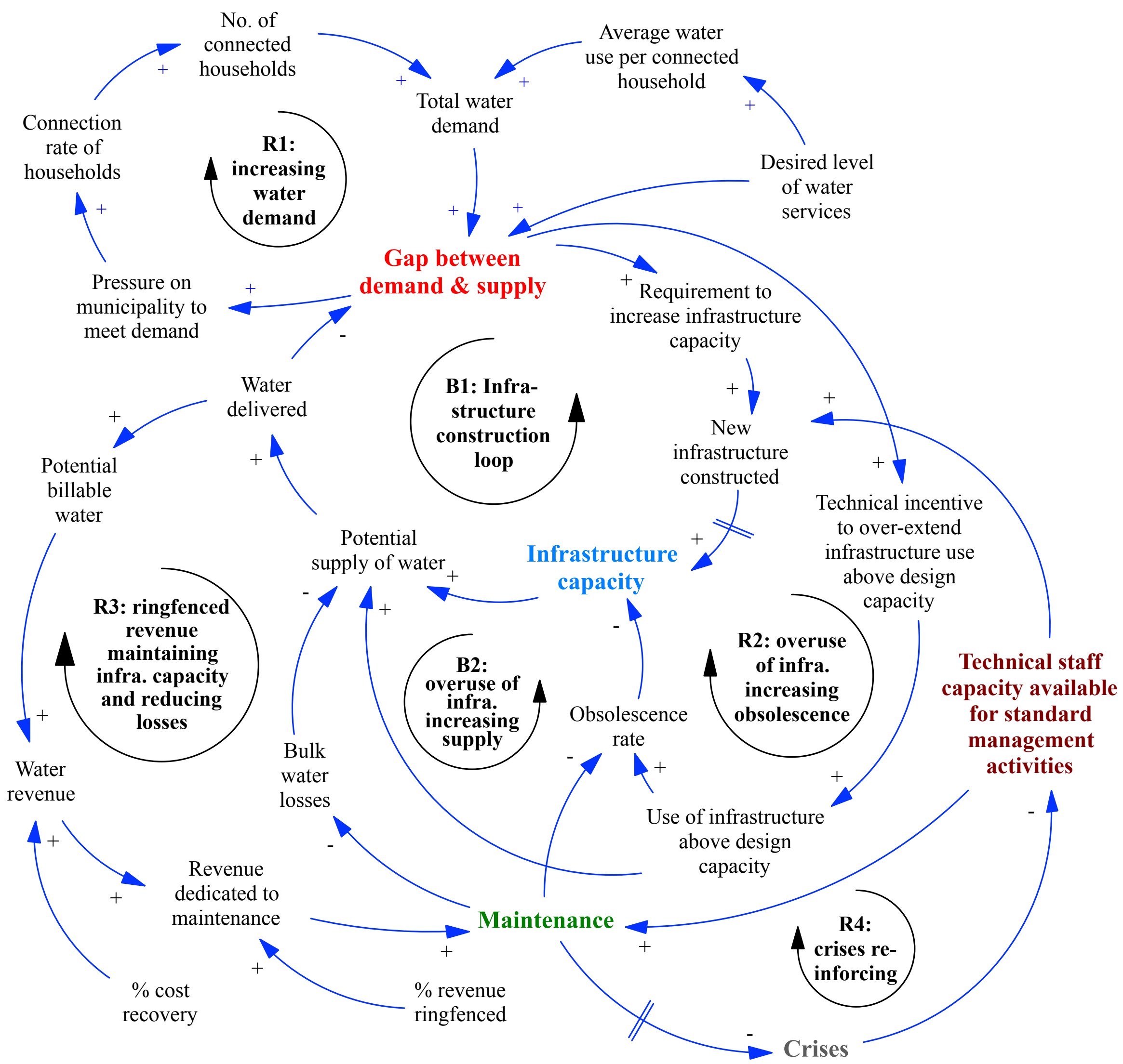

Figure 2: Aggregate causal loop diagram (CLD) for the 'modes of failure' model. Six feedback loops are identified in the CLD: two balancing loops (B1 and B2); four reinforcing loops (R1, R2, R3, and R4).

The second way in which the municipality meets the gap between supply and demand is through over-extending the current infrastructure above its design capacity. The 'Use of infrastructure above design capacity' allows the municipality to increase the quantity of potable water produced, and therefore increase the supply of water, which in turn decreases the gap between supply and demand (**B2: overuse of infrastructure increasing supply**). However, the over-extension of infrastructure carries the concomitant effect of increasing how fast municipal infrastructure decreases in value and use (the 'Obsolescence rate'). The longer water supply infrastructure operates above its design capacity, the quicker the infrastructure obsolesces, and the quicker it requires refurbishment and replacement. This is the second reinforcing feedback loop (**R2: overuse of infrastructure increasing obsolescence**).

The obsolescence rate is also influenced by municipal officials undertaking day-to-day maintenance as part of the operational regime of water service delivery. However, in practise the use of infrastructure above design capacity gives no room for maintenance as the plant is literally run to failure and only then is maintenance actually carried out. How much maintenance work can be accomplished is influenced both by the attention that the municipal staff can give and the revenue dedicated to maintenance, which is subject to the amount of revenue derived from providing water services. The more water delivered to users, the more the ‘Potential billable water’. Actual ‘Water revenue’ is determined by the proportion of billable water for which the municipality receives payment (‘% cost recovery’). Similarly, the ‘Revenue dedicated to maintenance’ is subject to the proportion of the ‘Water revenue’ that is reserved for this purpose (‘% revenue ringfenced’). By increasing the proportion of water revenue that is ringfenced, the municipality can perform more maintenance, and therefore reduce bulk water losses and the obsolescence rate, which enables more potable water to be delivered and in turn, increases the ‘Potential billable water’ (**R3: ringfenced revenue maintaining infrastructure capacity and reducing losses**).

The final feedback loop involves the ‘Technical staff capacity available for standard management activities’. In order to address ‘Crises’, municipal staff divert their attention away from standard activities towards immediately addressing these crises. Doing so reduces the capacity of the municipal staff to address standard technical activities, which reduces the amount of maintenance that can be performed. Over time, the accumulated lack of maintenance creates the conditions for new infrastructural crises to occur, which serves to further reduce the municipal staff capacity for standard activities. A reduction in these activities influences both the maintenance activities and the quantity of ‘New infrastructure constructed’ (by affecting strategic planning, grant sourcing, and other such activities that municipal officials perform in the process of constructing new infrastructure). This feedback loop (**R4: crises reinforcing**) is the primary endogenous driver of municipal crises explored in the *MoF* model. The following sub-section describes the structure of the simulation model that is based on the problem formulation in this CLD.

4.3. Specifying the structure of the simulation model:

The six sectors of the *MoF* model are:

1. Water demand of urban domestic and urban commercial users in Greater Kirkwood;
2. Water service delivery;
3. Infrastructure capacity;
4. Infrastructure maintenance;
5. Revenue; and
6. Technical staffing capacity within the SRVM.

The water demand sub-model features two stocks that accumulate the number of ‘unconnected’ and ‘connected’ households in the Greater Kirkwood area (see Figure A.1). The growth in the total number of households is influenced by municipal population and housing trends, which are modelled using data accounting for urbanisation. The total household water demand plus the additional demand from other urban users (including urban commercial users) gives the total water demand. The *MoF* model represents the municipality’s attempts to meet this total water demand via the ‘water service delivery’ sub-model. This second sub-model apportions the supply of water between the different user groups: unconnected households; connected households; and ‘other urban users’ (see Figure A.2). The difference between the demands of the different user groups, and the water delivered to the users according to the available supply, is calculated through a series of discrepancy variables. The variable ‘current total discrepancy’ is the sum of:

- The discrepancy in water delivered to unconnected households;
- The discrepancy in water delivered to connected households; and
- The discrepancy in water delivered to other urban users.

The variable 'current total discrepancy' drives the demand for additional infrastructure capacity, which influences the infrastructure sub-model that is at the heart of the *MoF* model (see Figure A.3). The infrastructure sub-model consists of three stocks linked in an aging-chain model structure. The first stock represents the required additional infrastructural capacity, the second stock calculates the infrastructure under construction and refurbishment, whilst the third stock accounts for the total infrastructure capacity. The infrastructure sub-model includes:

- The effects of staff capacity constraints on initiating and completing the refurbishment and construction of new infrastructure;
- A decision-rule that when there is a discrepancy between the demand for water and the supply of water (and the municipality therefore requires additional capacity), then municipal supply infrastructure is over-extended above its design capacity in order to meet the additional capacity requirements;
- The effects of the above-mentioned decision-rule on the rate at which infrastructure obsolesces; and
- The effects of maintenance on obsolescence.

The maintenance sub-model both influences, and is influenced by, the infrastructure sub-model (see Figure A.3). The quantity of required maintenance is calculated against the infrastructure capacity stock (using an aggregated estimate of the quantity of infrastructure capacity requiring annual maintenance in order to maintain optimum performance). The crux of the maintenance model is the variable 'potential maintenance', which is the point at which the financial constraints on maintenance interact with the constraints on maintenance placed by shortfalls in technical staff capacity. Here technical staff capacity refers both to the number and expertise level of the staff. The financial constraints on maintenance are determined in the revenue sub-model of the *MoF* model (see Figure A.5). The staff capacity constraints on maintenance are calculated in the staffing sub-model (see Figure A.6), which additionally influences the infrastructure construction and completion rates. The empirical relationships between the variables and sub-models introduced here are detailed in the Appendix A.

5. Applying the model to the September 2014 protests in Kirkwood

5.1. Model settings and verification:

A 20-year simulation period (2001-2021) was selected to account for when the SRVM began operating through to the manifestations of the service delivery problems in Greater Kirkwood between 2009 and the 2014. The period between 2001 and 2014 was used primarily for model calibration purposes, whilst the period between 2014 and 2021 was used for projection and policy analysis purposes.

The model was verified in three ways: firstly, the consistency between the conceptualisation of the model (presented in the CLD sub-section above) and the specified simulation model was checked; secondly, unit consistency and the real-world interpretation of the units was checked manually and then using the 'Unit Check' function in Vensim; thirdly, the model was numerically stable under its model settings. A time step of 0.007815 years (less than a week) was selected. The model was simulated in Vensim DSS (v.6.3 for Macintosh) using the time unit of years, with the Euler method selected for numerical integration purposes. Rather than relying on one data set, the model was tested against historical data from a range of sources, collected by national, provincial and local authorities. The results presented below reflect the model outcomes that accord with historical data and experiences.

5.2. Reference mode:

The reference mode simulation represents the system behaviour that culminated in the protests and fires in Kirkwood in September 2014. The population living in connected households in the Greater Kirkwood region sharply increases from mid-2005 onwards, with an associated decrease in the population size of individuals living in unconnected households (see Figure 3(a)). As the population living in connected households increases, the quantity of potable water delivered to these households almost doubles (as seen in the period between 2005 and 2009 in line 1 of Figure 3(b)). The quantity of potable water delivered to unconnected households (line 2 of Figure 3(b)) decreases in this same period, reflecting the changing demographics of the region.

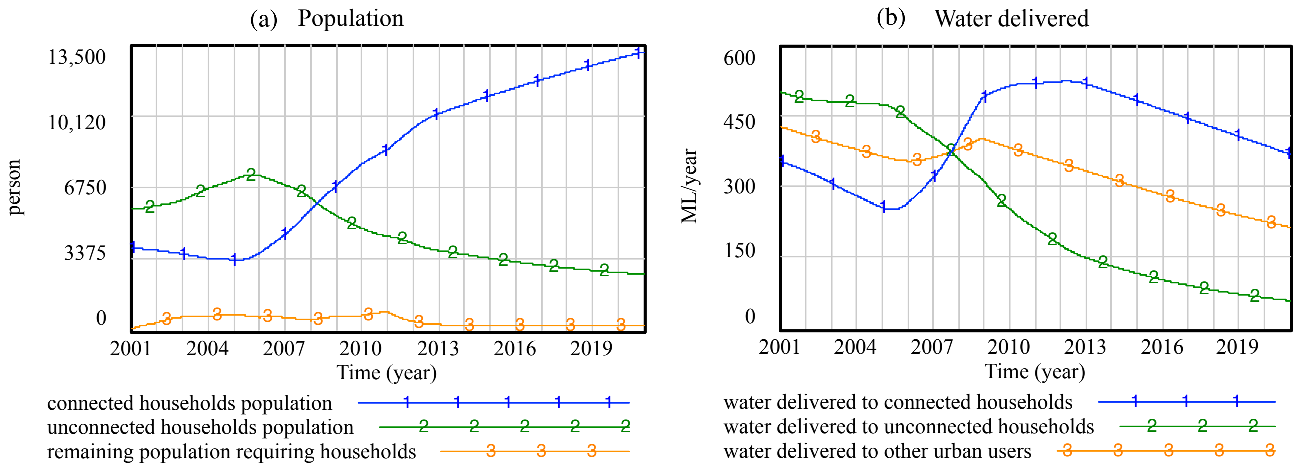

Figure 3: Reference mode behaviour for population (a) and water delivered (b).

The amount of water delivered to users in the region, as represented in Figure 3(b), is contingent on the available water supply. Figure 4(a) shows the supply of water increasing between 2006 and mid-2009 as a result of the actual production (line 3) increasing to a total of 30% over the designed infrastructure capacity. In real terms, infrastructure capacity declines in this same period (line 2 in Figure 4(a)). The supply of water (line 1) remains significantly lower than actual production due to bulk water losses throughout the water supply scheme (which are held at an average of 30% over the simulation period).

Figure 4(b) compares the total water demand in Greater Kirkwood (line 1) in relation to the gap between this demand and the total water delivered (line 2). The gap between the water demand and the water delivered is represented in the *MoF* model as a total discrepancy. As Figure 4(b) shows, municipal infrastructure can adequately meet demand until 2005, after which the discrepancy begins to rise. This discrepancy grows to around 200 ML/year, where it stabilises until 2009 (as a result of infrastructure being over-extended beyond its design capacities). After 2009, the discrepancy then increases exponentially as the gap between the demand and the supply of water burgeons, and as infrastructure is continually used above its design capacities.

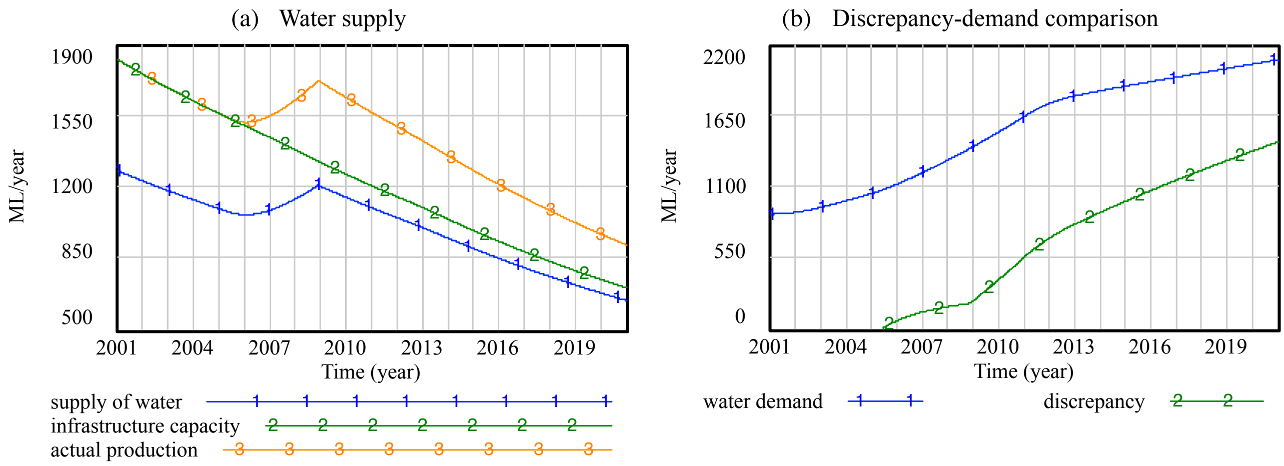

Figure 4: The left-hand graph (a) shows the reference mode behaviour for water supply; the right-hand graph (b) compares the total water demand (line 1) to the discrepancy (line 2), which is the gap between the demand and the water delivered.

The rate at which water supply infrastructure obsolesces is shown in line 1 of Figure 5(a), where it is compared to the overall maintenance that the municipal officials can perform (line 2). The decreasing trend in the obsolescence rate from 2001 to 2006 reflects the general decrease in infrastructural capacity over this period, when little refurbishment or construction of new infrastructure occurred, but infrastructure continued to obsolesce.

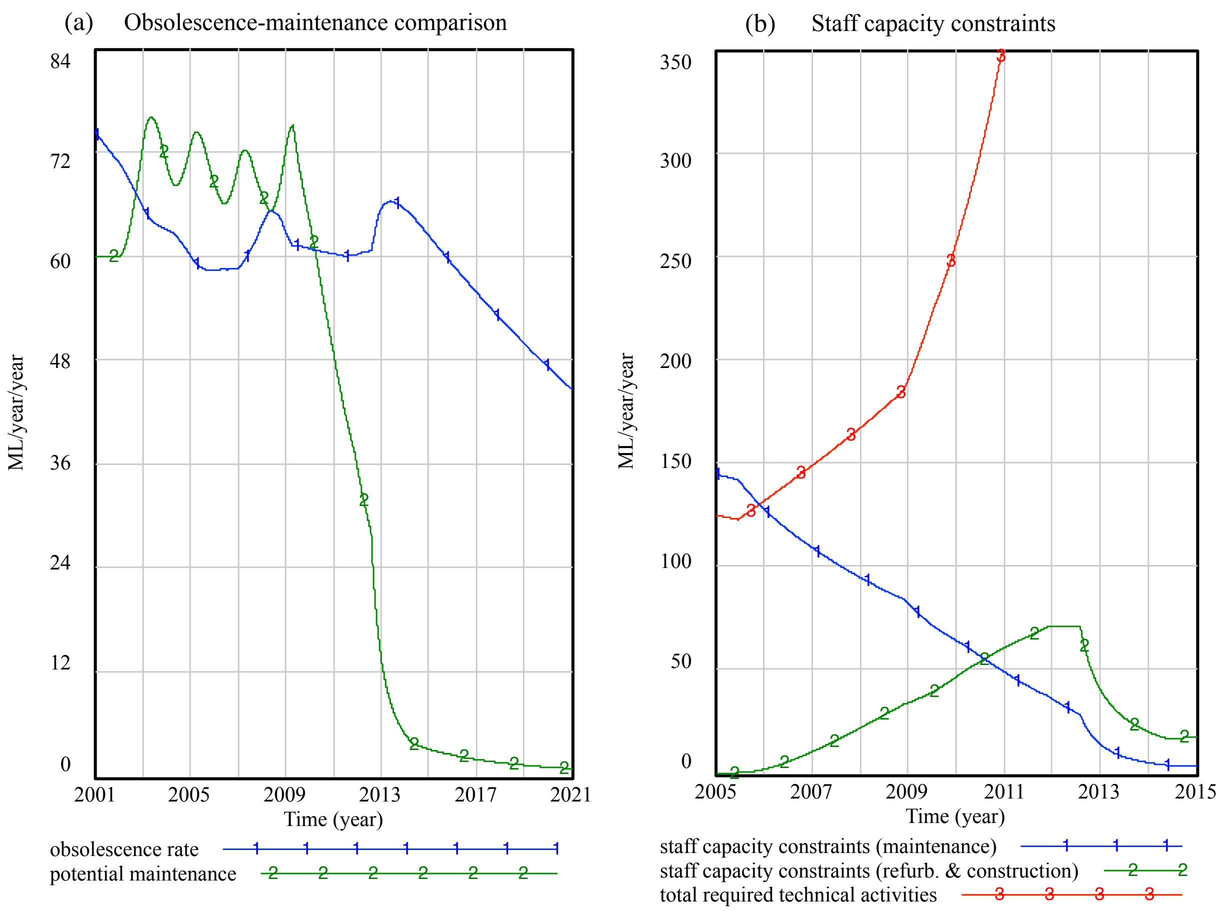

Figure 5: Comparison of the obsolescence rate and the overall maintenance that can be performed is displayed, termed 'potential maintenance' (left-hand graph (a)); the right-hand graph (b) compares the constraints on staff capacity in the reference mode in a time segment from 2005–2015, in relation to the total required technical activities.

The effect of over-extending infrastructure beyond its design capacity is visible in the period between 2006 and 2009 in line 1 of Figure 5(a), which shows the water supply infrastructure obsolescing at an increasing rate of 58 to 65 ML/year. Line 2 of Figure 5(a) shows the overall maintenance performed by the municipal officials (termed the ‘potential maintenance’), which oscillates around 70 ML/year between 2001 and early-2009 (after which the amount of maintenance that can be performed decreases sharply). As noted in sub-section 4.3, ‘potential maintenance’ is the crux of the maintenance sub-model (because it is the variable at which the financial constraints on maintenance interact with the constraints on maintenance placed by shortfalls in technical staff capacity). Line 1 of Figure 5(b) shows that sufficient technical staff capacity existed to undertake maintenance until early 2009 (meaning that the primary constraints on maintenance between 2001 and 2009 were financial in nature). Line 3 of Figure 5(b) shows the total number of required technical activities as exponentially increasing from 2005 onwards (in response to the growing discrepancy represented in line 2 of Figure 5(a)).

5.3. The situation with no infrastructure overuse?

What would have happened if municipal technical staff had only operated its water supply infrastructure according to its design capacity? This situation was explored in the *MoF* model by adjusting the ‘maximum over-design capacity factor’ (*MOCF*) downward from 1.3 to 1 (see equation 13 in Appendix A for technical details). In a situation of ‘no infrastructure overuse’, the actual production of water would be kept within the design capacities of the relevant infrastructure. The results of this course of action are visible in a decreasing supply of water, as shown in Figure 6(a). Between 2006 and 2009, the supply of water increases in the baseline simulation, as infrastructure is over-extended (line 1 of Figure 6(a)), whereas the supply of water decreases more rapidly in the ‘no infrastructure overuse’ situation (line 2 of Figure 6(a)).

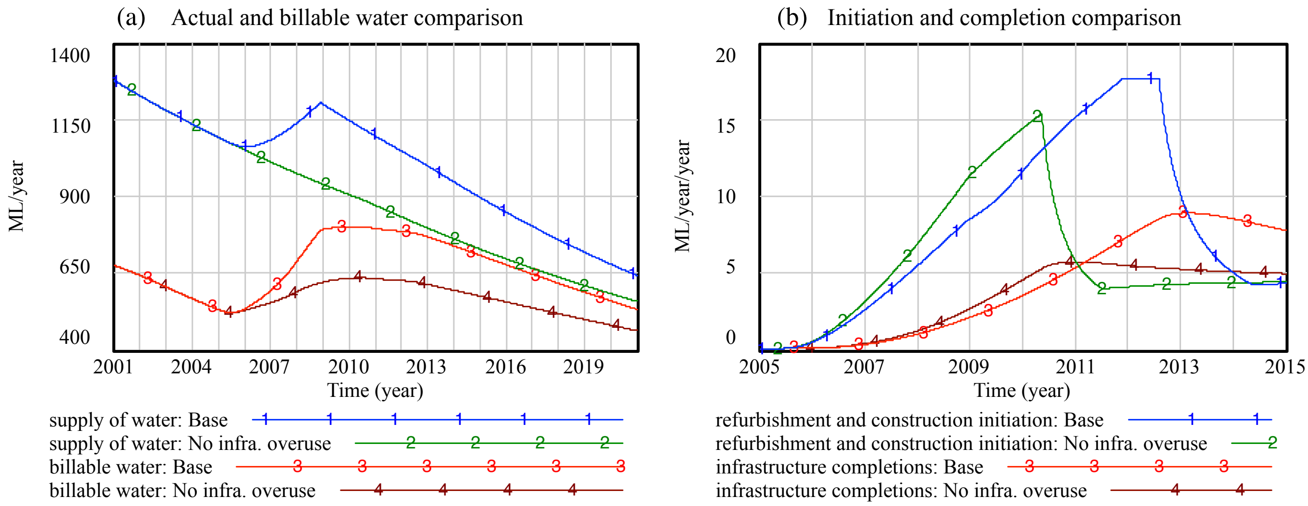

Figure 6: Comparison of the base and ‘no infrastructure overuse’ situations: (a) compares the actual supply of water and the billable water in both situations; (b) compares the rate of ‘initiation of refurbishment and construction’ to the rate of infrastructure completion on the Greater Kirkwood water supply scheme in a time segment from 2005–2015.

One of the motivating factors for the municipality over-extending infrastructure is illustrated in the comparison of ‘billable water’ (lines 3 and 4 in Figure 6(a)). In the baseline simulation, a sharp increase in the total quantity of billable water is evident between 2006 and 2009 (line 3), which is a secondary effect of the greater quantity of water delivered to ‘billable users’ (i.e.

connected households and other urban users). The greater the quantity of billable water, the greater the potential water revenue (depending on the efficacy of cost recovery measures). Hence, Figure 6(a) shows one of the possible incentives to over-extend infrastructure as being the production of greater quantities of billable water (and therefore the maintenance of this revenue stream for the municipality). By only producing water within the design constraints of infrastructure (as in line 2 of Figure 6(a)), the municipality can supply less potable water to meet the rising demands from 2005 onwards. In a situation of 'no infrastructure overuse', the municipality would therefore need to initiate refurbishing and constructing infrastructure earlier than in the baseline simulation (see lines 1 and 2 in Figure 6(b)). As line 2 in Figure 6(b) shows, the initiation rate falls sharply in mid-2010 in spite of the increased demand and the earlier initiation. This behaviour is the result of service delivery crises increasing as the discrepancy grows. The *MoF* model simulates the effects of service delivery crises as influencing the total required technical activities of municipal staff (as they need to increasingly fire-fight urgent service delivery crises). Figure 7(a) shows that the total required technical activities increase in the 'no infrastructure overuse' situation two years earlier than in the baseline simulation. In effect, this means that despite the earlier initiation of refurbishment and construction, the long-term effect on infrastructure capacity is marginal (as shown in Figure 7(b). Therefore the short-term fix fails in the long-term.

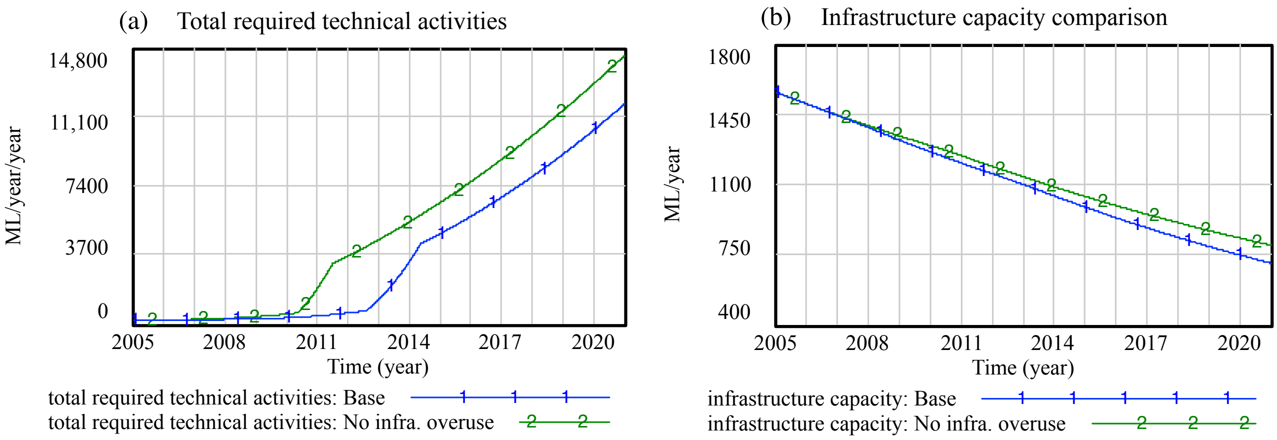

Figure 7: Comparison of the 'total required technical activities' between the baseline simulation and the 'no infrastructure overuse' situation (a); the right-hand graph (b) compares the infrastructure capacity across the two simulations (both graphs showing a time fragment from 2005-2021).

5.4 Validation and sensitivity analysis:

The reference mode successfully captures the historical behaviour until 2011 and explains the underlying mechanisms that resulted in the protests and fires of 2014. A coping strategy employed by municipal officials of overusing infrastructure is shown in the simulation 'no infrastructure over-use' to only delay the inevitable. The same underlying mechanisms ensure the eventual modes of failure.

The question now arises, can any policy mitigate these modes of failure? A sensitivity analysis was undertaken to explore the answer to the latter question. Sensitivity analysis forms a part of model validation, which strives to increase confidence in the robustness of the simulated results and the policy analysis arising out of the modelling process (Sterman, 2000). Sensitivity analysis offers a way of exploring which uncertain parameters lead to major changes in the model results (Ford, 2009). The details of a univariate sensitivity analysis, in which seven parameters were varied over a wide range of uncertainty, can be found in the supplementary material. The sensitivity analysis demonstrated that staffing capacity exerted a constraining effect over the longer term, and that only minor changes occurred in infrastructure capacity. In summary, no individual measure was found to be effective in addressing the fundamental model behaviour of declining infrastructural capacity.

6. Discussion and conclusion

In this modelling paper, a number of interlinked 'modes of failure' in the water service delivery function of local government in South Africa are identified:

1. The overuse of infrastructure increasing the obsolescence rate (R2 in Figure 2);
2. Lack of pro-active infrastructure planning coupled with a lack of systematic maintenance, including fixing water leaks (B1 in Figure 2);
3. The 'fire-fighting' reaction of municipal staff to service delivery crises, which causes their attention to deviate from performing systematic maintenance and pro-active infrastructure planning (R1 and B1 Figure 2);
4. Limited financial means and a lack of ringfencing of water-related revenue for the maintenance of infrastructure (R3 in Figure 2);
5. Infrastructural capacity inadequate for addressing water demand (B1 in Figure 2); and
6. Inadequate technical staffing capacity limiting the performance of systematic maintenance and pro-active infrastructure planning (part of R4 and constraining B1 in Figure 2).

For instance, the first mode of failure reflects what Repenning and Sterman (2001) call the 'capability trap'. Given that there is a substantial delay "between cutting corners and the consequential decline in capability" (*ibid*., 72), supervisors and managers reap the benefits of increased output from a particular system whilst saving on maintenance costs. However, as time goes on, and as equipment ages, managers are faced with lower yields and longer downtimes, which is a pattern of behaviour that has been identified in cases across production management and industrial engineering (*ibid*.). The behaviour of 'cutting corners' and 'taking shortcuts' was manifested in the Kirkwood case first as the overuse of infrastructure as a short-term fix, and then as a rational response of municipal staff to the increased pressure in their working environment (i.e. 'fire-fighting', the third mode of failure).

The six modes of failure derived through this modelling approach resonated with municipal technical officials who had participated in the SANPAD research project. This was exemplified when an adapted version of the modes of failure CLD (Figure 2) was co-presented by a researcher and a senior municipal official. The setting for this presentation was the national-level 'Water Dialogue' initiated by the Water Research Commission of South Africa and attended by senior representatives from national government departments. The systemic nature of the modes of failure of local government was explained to national policy makers. The image of Kirkwood burning in the September 2014 protests was recognised as a warning of how the endogenous drivers of failure could play out in many more of the small towns of South Africa. As such, this modelling endeavour succeeded in clarifying the socio-technical problem and was an effective tool in communicating the causes of local water services systems failure to a national audience.

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