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11 Modelling in the 'Muddled Middle': A Case Study of Water Service Delivery in Post-Apartheid South Africa

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Abstract: The governance and management of water in post-apartheid South Africa has been significantly redesigned by national government in the two decades since institutional apartheid formally ended. The redesigning efforts have aspired towards decentralised decision-making, participatory governance and management, and the integration of multiple issues that have social, environmental, and technical dimensions. However, the failures in implementation have led to many commentators to point-out the gap between the policy aspirations and the operational realities on the ground. This chapter focuses on the governance and management of municipal water services to motivate for the use of a modelling approach that explores the ambiguous 'muddled middle' between policy design, implementation and adaptation. The modelling approach involves an ethnographically-embedded form of participatory system dynamics modelling, which was applied by the authors in an action research process. The modelling approach is held to be relevant for exploring controversial and complex case studies that offer representative and extreme examples of systemic dysfunction, where policy-level analytical objectives co-exist with action research imperatives of employing tools and methods to understand (and where possible, address) stakeholders' issues of concern.

Keywords: Action research; local government; participatory modelling; methodological hybridization; South Africa; system dynamics; transdisciplinarity; water management; water scarcity

11.1 Introduction

At the centre of the South African water law reform process initiated by the first democratic government in 1994 lay the challenge of managing water differently from the way it was managed under apartheid (Rowlston 2011). This process culminated in the promulgation of the National Water Act of 1998 and the Water Services Act of 1997, which are regarded internationally as ambitious and forward-thinking instances of legislation that reflect the broad aims of Integrated Water Resource Management (IWRM) (Schreiner 2013). The local government sector was also redesigned in the first decade of democracy, with extensive powers and autonomy granted to the sector under a policy of Developmental Local Government (DLG) (Republic of South Africa (RSA) 1998). Both DLG and IWRM aspire towards decentralised decision-making, participatory governance and management, and the integration of multiple issues that have social, environmental, and technical dimensions. However, both IWRM and DLG have been criticised for implementation failures in post-apartheid South Africa (Mehta et al. 2014; Siddle & Koelble 2012), which have led to proposals from national government that water policy needs to be redesigned (Department of Water Affairs (DWA) 2013) and that local government powers and functions should be re-assessed (Department of Water and Sanitation 2014).

This chapter focuses on the governance and management of water services (the primary intersection between the legislative frameworks for local government and those for water management and water service delivery) to motivate the use of a modelling approach to explore the ambiguous 'muddled middle' between policy design, implementation and adaptation. The modelling approach involves an ethnographically-embedded form of participatory system dynamics modelling. This chapter applies the modelling approach to a case study, drawing on the authors' extended participation in an action research process involving water services in the Sundays River Valley Municipality (SRVM) in South Africa (SA).

11.2 The case study

The SRVM contains a relatively small population of 54500 people and is located in the impoverished Eastern Cape province (Statistics South Africa 2014). The SRVM is a primarily rural municipality with a number of small urban settlements interspersed between large commercial farms and nature reserves. The local government authority of the SRVM is responsible for providing water services to all urban water users within its jurisdiction. As of 2010, 47% of the population subsisted on a household income of less than R800 per month (approximately US$80), with unemployment estimated at 44% (SRVM 2010). Almost half of the municipal population is therefore reliant on social grants from national government and on receiving free basic services (including water and sanitation) from local government. Over a third of South African municipalities are of a similar size and socio-economic character to the SRVM. Despite this representative quality, in many respects, the SRVM is also an extreme case: in 2010, national and provincial government departments initiated intervention processes in the SRVM, following an extended period of financial mismanagement and bankruptcy in which the provision of water services became increasingly erratic and unreliable. In spite of extensive government interventions, the area continued to face declining water services with disastrous effect. In September 2014, a series of violent service delivery protests broke-out in the main town of Kirkwood, where municipal offices and infrastructure were set alight by protestors and burned to the ground (South African Press Association [SAPA] 2014). The SRVM case therefore offers both extreme and representative aspects of the water challenges faced by local authorities in post-apartheid SA (Clifford-Holmes 2015; Clifford-Holmes et al. 2016), which, following Yin (2009), provided the rationale for employing the 'single case design' utilised in the study.

The modelling approach described in this chapter evolved out of an action research project funded by the South Africa Netherlands Research Programme for Alternatives in Development (SANPAD), entitled 'From policy to practice: enhancing implementation of water policies for sustainable development' (Palmer et al. 2014). The SANPAD project adopted a transdisciplinary stance and used a range of theories, methods, approaches and practices in novel ways, with the aim of testing their usefulness in breaching barriers impeding the implementation of IWRM in SA. Through the action research process, it became evident that the SRVM was a representative case of a South African region facing what Ohlsson (1999) terms 'second-order scarcity'. Water scarcity is frequently more than a function of demand outstripping supply resulting in physical 'first-order' scarcity. In contrast to the latter characterisation of scarcity, Ohlsson (1999) construes of second-order scarcity as a given social entity's lack of adaptive capacity. In applying this concept to water in SA, Tapela (2012) argues that 'social water scarcity' occurs when a confluence of factors – including insufficient finances, human capabilities, and political will – results in the provision of water services failing to meet a growing demand. Given the abundance of raw (untreated) water in the SRVM, shortages of potable (i.e. drinking-quality) water are clearly a case of second-order scarcity in general, and what Tapela (2012) refers to as 'social water scarcity' in particular. Given this social water scarcity, modelling approaches that contain multiple social dimensions (as to how the modelling is both undertaken and used) were found to be valuable in the SANPAD action research process in the SRVM. The following section locates the way in which modelling was undertaken and used in this study in relation to the broader literature on modelling in the water sector.

11.3 Contextualising modelling in the 'muddled middle' in the water sector

In reviewing the multiple roles that models perform in the water sector, Hare (2011) uses the distinction of Haag and Kaupenjohann (2001) between modelling for scientific research purposes (primarily for forecasting and prediction) and modelling to support policy- and decision-making, noting that it is the latter category that particularly requires stakeholder participation. Within engineering communities, modelling is often used to support design processes and in doing so, engineering modelling can be distinguished from scientific modelling (Bissell & Dillon 2012; Epstein 2008; Elms & Brown 2012). Modelling is useful to engineers as a tool to support causing 'the best change in an uncertain situation within the available resources' (Koen 2003, p. 24). System dynamics (SD) is one approach that has emerged as useful for a range of these modelling purposes. SD is defined here as 'a way of modelling peoples' perceptions of real-world systems based especially on causal relationships and feedback' (Mingers & Rosenhead 2004, p. 532). Within the water sector, the themes that have traditionally garnered the greatest attention of SD modellers are those of regional planning and river basin management, and flooding and irrigation (as reviewed in Winz, Brierley, & Trowsdale 2009). In the last decade, SD has also increasingly been used to investigate the challenges associated with urban water supply (as seen in studies on municipal water conservation policies (Ahmad & Prashar 2010); urban drinking water supply (Xi & Poh 2013); and urban wastewater management (Rehan et al. 2014)). The use of SD modelling is on the increase throughout the 11 countries in Southern Africa, as shown in a systematic review of scientific literature published between 2003 and 2014 (Brent et al. 2016). More specifically, SD has a long and diverse history of use in developmental planning, strategic management, and mediation and brokerage in the South African water sector (Clifford-Holmes, Slinger & Palmer 2016).

Practitioners of SD have been criticised for over-simplifying the 'problem definition' stage of the modelling process; for reducing 'problematic situations' (where various problems must be dealt with at the same time) to single 'problems'; and lastly, for offering few methodological details on how policies derived and tested through SD process can be implemented in the real world (Rodríguez-Ulloa, Montbrun, & Martínez-Vicente 2011). However, a number of approaches to stakeholder-engaged SD modelling have developed in the last decade, partly in response to the above limitations. A well-developed approach is 'group model-building' (Vennix 1999; Rouwette & Vennix 2006), which aims to build or come to a group understanding of a complex problem. Other examples of stakeholder-engaged modelling in the water sector that employ SD include:

- Participatory model building (Langsdale 2007; Stave 2010);
- Cooperative modelling (Cockerill, Passell & Tidwell 2006; Tidwell et al. 2004); and
- Mediated modelling (van den Belt 2004).

Critics argue that whilst the above-mentioned approaches incorporate mental modelling and social learning, SD still remains functionalist in nature: given that SD 'sees system structure as the determining force behind system behaviour and tries to map that structure in terms of the relationships between feedback loops' (Jackson 2003, p. 81), it fails to account for the 'innate subjectivity of human beings' (Flood & Jackson 1991, p. 79). Accordingly, the theory, methodology and methods of SD have been judged by some critics as unsuitable to the subject matter of its concern: 'human beings, through their intentions, motivations and actions, shape social systems… [hence] we need to understand the subjective interpretations of the world that individual social actors employ' (Jackson 2003, p. 80). By trying to study social systems 'objectively', SD 'misses the point [because] social structure emerges through a process of negotiation and renegotiation of meaning' (*ibid.*).

If the above criticisms hold true, then SD modelling is poorly suited in social systems. The approach taken in this study can be situated in relation to three responses to the latter 'SD is structure-focused' critique. The first response is the one posited by critics from within the broader systems thinking field. Instead of relying on SD to 'do everything', Jackson (*ibid.*) argues that 'a critical systems thinker is likely to want to combine the strengths of [SD] with what other systems approaches have learned to do better'. One such approach is Soft Systems Methodology (SSM), which provides qualitative tools and techniques for exploring diverse perspectives on a problematic situation whilst addressing 'the socio-political elements of an intervention' (Lane & Oliva 1998, p. 214). The SSM approach is based on an interpretative perspective of social settings, in which humans are understood to 'negotiate and re-negotiate with others their perceptions and interpretations of the world outside themselves' (Checkland 1981, p. 283-284). Several attempts have been made to integrate SD with SSM. 'Holon dynamics', for example, promotes using SSM to generate multiple perspectives on a problematic situation before studying it further using SD (Lane & Oliva 1998). Similar approaches have been advocated in SD textbooks (see Maani & Cavana 2007) and have been formalised into an integrated framework called 'Soft System Dynamics Methodology' (Rodríguez-Ulloa & Paucar-Caceres 2005). Rodriquez-Ulloa, Montbrun, and Martinez-Vicente. (2011) is one of the only published applications of the latter integrated approach.

An alternative approach is to use SD in combination with other 'problem structuring methods' (Mingers & Rosenhead 2004), which is the second response to the 'SD is structure-focused' critique. Problem structuring methods (PSMs) are useful in engaging wicked problems that are characterised by multiple actors and perspectives, with incommensurable or conflicting interests, and key uncertainties. As such, PSMs should 'operate iteratively… [and] enable several alternative perspectives to be brought into conjunction with each other' (*ibid*., p. 531). Horlick-Jones and Rosenhead (2007) report on research and consulting practice that combined ethnographic tools with various PSMs, referring to this combination as a form of 'methodological hybridisation' (*ibid.*, p. 588). Ethnographic tools and perspectives call to attention the subjective interpretations of the world that individual social actors employ. This focus on agency can serve as a counter-balance to the focus on structure that is arguably central to SD.

The third response directly rebuts the critique that 'SD is structure-focused'. This rebuttal positions SD as beginning from the perspective of stakeholders' activities, recently exemplified in Olaya's (2015) motivation of 'operational thinking' as being key to the way in which SD modelling is undertaken. Rather than modelling being bound by available data and the requirement to fit a model's simulations to historical behaviour, SD is explicitly stakeholder-centred, drawing data from a broad range of sources (Ford 2009). Central to this way of modelling is the exploration of questions like 'who are the actors in the dynamics of a complex system and how do their perceptions, pressures and policies interact?' (Richardson 2011, p.229). SD practitioners – including Lane (2000), Richardson (2011), and Olaya (2015) – are united in their arguments that SD is a non-deterministic approach that ascribes to human beings the capacity to invent (and reinvent) their own futures, whilst acknowledging that this capacity (i.e. agency) is circumscribed by structural conditions. Seen in this way, the orientation of SD towards the structure-agency debate within the social sciences is consistent with the sociological theory and practice advocated by Layder (1998). Rather than conceiving of a structure/agency dualism, Layder (*ibid*) posits a 'middle way' as a dialectical understanding of the co-existence and interrelationship of structure and agency.

This chapter reports on a modelling approach that drew strands from each of the three responses to the 'SD focuses-on-structure' critique. The approach conceived of stakeholders as influencing 'who gets what water, when and how… between the aspirational policy realm and the practical realities on the ground' (Clifford-Holmes et al. 2016, p.5). This space between the clean lines of policy design (how we want things to work) and the messy operational reality of implementation was conceived as 'the muddled middle' *(ibid).* 'Modelling in the muddled middle' referred to the conscious choice to engage with stakeholders in the messy reality they face and to employ modelling tools and research methods in seeking to understand (and where possible, address) their issues. Following Vriens and Achterbergh (2006), SD models were conceived as being made *of* social systems; built *in* social systems; and built *for* social systems, whilst recognising that modelling can perform many functions and be undertaken for multiple purposes (Epstein 2008). Rather than conceiving of, and undertaking, modelling as a standalone analytical activity, the approach described in this chapter combined SD with institutional analysis and ethnographic tools in a form of methodological hybridisation, as outlined in the following section.

11.4 Methods

The case and context of this study were summarised in section 12.2, which introduced the broader research project within which this study was nested (described further in Palmer et al. 2014.; Molony 2015; Muller 2013; Clifford-Holmes 2015). In order to address the aims of this study, a multi-method research approach was employed, which drew on institutional, ethnographic, and systems analyses within an evolving, transdisciplinary methodology (Wickson, Carew & Russell 2006). As part of the single case study research design, qualitative and quantitative data were collected via participant observation, direct observation, semi-structured interviews, and from documentary and archival sources. Ethnographic analysis was performed following extended fieldwork in the SRVM, which was undertaken between 2011 and 2012, with follow-up visits for workshops and meetings between 2012 and 2014. This fieldwork and the associated analysis allowed for a detailed and multi-layered understanding of water services challenges in the SRVM to develop (Clifford-Holmes 2015), with a focus on the practical activities of water management (Agnew 2011). The challenges of municipal water supply in the SRVM were found to 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 was selected as an ideal method for exploring these practices and the problems to which they give rise, particularly at the strategic level (Sterman 2000), for the multiple reasons explored in section 11.3. Rather than building one large model, a portfolio of small models was developed, using the standard modelling process outlined in SD textbooks of problem scoping; formulating a dynamic hypothesis using qualitative causal loop diagrams and by specifying a stock-flow structure; then estimating parameters and initial conditions before building and testing a simulation model (Maani & Cavana 2007; Ford 2009; Sterman 2000). The four SD models developed in this study are summarised in Table 11.1. The first model was primarily undertaken as an initial scoping exercise with little stakeholder engagement, as such, this first model is not discussed here (for details, see Clifford-Holmes 2015). The next three models were developed through a process of system exploration, where different stakeholder groups were engaged in settings where they were at ease, rather than consensus building in multi-stakeholder workshops (as in Group Model-Building). Hence, the SD models were developed as system understanding grew over the course of the research period between April 2012 and March 2015 (see Table 11.1), with the models being co-validated with stakeholder groups rather than being co-constructed. The following section describes the dialectical process by which three out of the four models were constructed and used as part of a broader action research process.

	Model name	**Model acronym**	**Timeframe**	**No. of stock variables**	**No. of feedback loops**	**Model documentation**
1	The Cooperatives Model	*CoOP*	April – Sept. 2012	20 (16.5%)	20	'Appendix D' of Clifford-Holmes (2015)
2	The Greater Kirkwood Water Supply model	*GKWS*	Nov. 2012 – July 2013	13 (10.3%)	71	(D'Hont 2013; D'Hont, Clifford-Holmes, & Slinger 2013) + 'Appendix E' of Clifford-Holmes (2015)
3	The Kirkwood Water Demand model	*K-DEM*	Aug. 2013 – March 2014	6 (7%)	13	(Clifford-Holmes et al. 2014) + 'Appendix F' of Clifford-Holmes (2015)
4	The Modes of Failure model	*MoF*	Jan. 2014 – March 2015	9 (9.3%)	143	(Clifford-Holmes et al. 2015)

Table 11.3 Summary of the four models, displayed in terms of the number (no.) of stock variables (with the relative percentage of the stock variables in relation to total variables in brackets); the number of feedback loops; and references for model documentation.

11.5 Results

The results of the 'modelling in the muddled middle' approach are described here in terms of which stakeholders were engaged, with what model, in which settings, and in what part of the modelling process. The models themselves are described and presented in increasing levels of detail in Clifford-Holmes (2015), as referenced in Table 11.1, and are introduced here with reference to the causal loop diagram (CLD) in Figure 11.1.

The driver of the system presented in Figure 11.1 is the 'Gap between demand & supply'. This gap *increases* with the 'Total water demand' and *decreases* with 'Water delivered'. The standard municipal response to this gap is to adjust the infrastructure capacity, through refurbishing current infrastructure and constructing new infrastructure. With 'New infrastructure constructed', the total 'Infrastructure capacity' increases after a delay that accounts for the construction lead time (diagrammatically represented in Figure 11.1 by the two lines on the arrow between these variables). With the capacity increasing, the 'Supply of water' and the 'Water delivered' can increase. This is the first balancing loop in the CLD (**B1: Infrastructure construction**). The Greater Kirkwood Water Supply model focused on exploring the operational particularities of infrastructure capacity in the modelled system.

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, p. 3), indicating that the gap between demand and supply resulted in 'Pressure on [the] municipality to meet demand' by increasing the 'Connection rate of households'. The greater the total number of 'Connected households', the greater the total water demand and the greater the 'gap between demand and supply', which forms a reinforcing feedback loop (**R1: water demand**). The Kirkwood Water Demand model explored this aspect.

The rate at which infrastructure decreases in value and function (therefore requiring refurbishing or replacing) is referred to as the 'obsolescence rate', which is influenced by municipal officials undertaking day-to-day maintenance as part of the operational regime of water service delivery. How much maintenance work can be accomplished is influenced both by the attention that the municipal staff can give to maintenance and the revenue dedicated to maintenance, which is subject to the revenue derived by providing water services. The more water delivered to users, the more the 'Potential billable water'. By increasing water revenue, the municipality is able to 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' (**R2: effect of revenue on maintenance and losses** – explored in the Modes of Failure model).

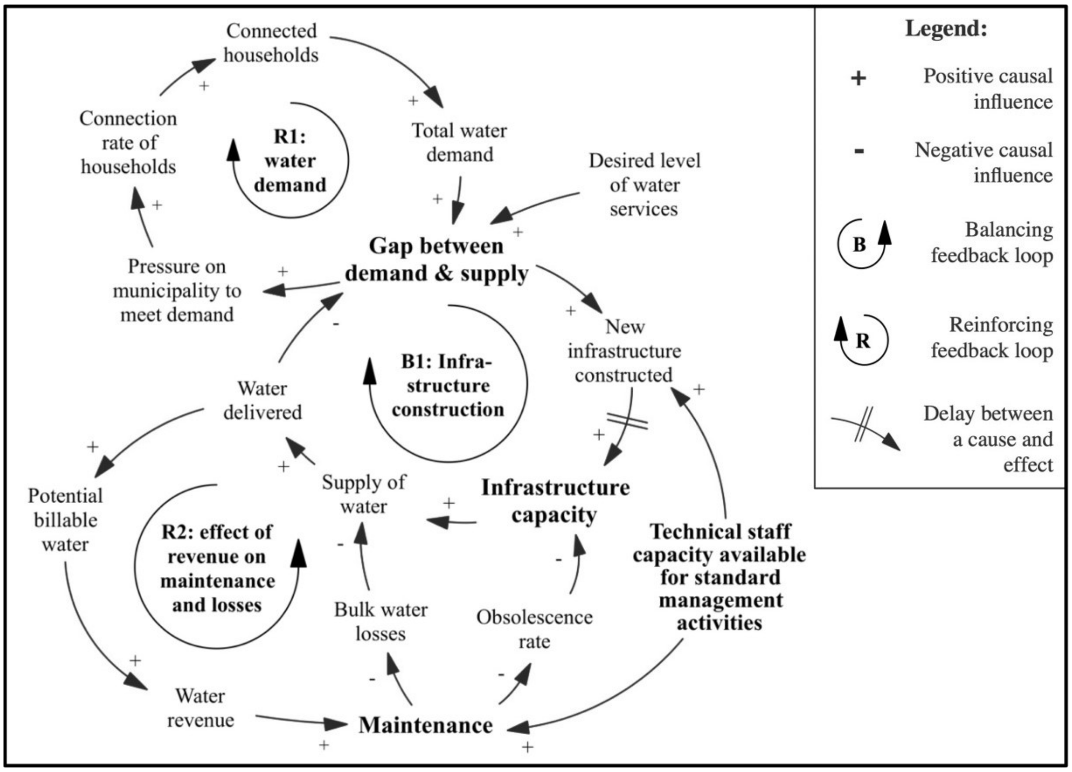

Figure 11.3 Overview causal loop diagram, with three feedback loops identified. Adapted from Clifford-Holmes et al. (2015, p. 6).

At a workshop facilitated by SANPAD researchers in 2012, it emerged that different actors had different understandings of the physical limitations of the Greater Kirkwood water supply scheme. The two central actors were the municipality (the SRVM) and the Lower Sundays River Water User Association (L-WUA), which was the bulk water supply agent to the municipality (see Clifford-Holmes et al. 2016). The differing views of these actors presented the opportunity to develop a model on the Kirkwood water supply scheme, where the process of model building (and the model itself) could be used for analytical purposes and as part of the on-going process of facilitation and action research. One of the advantages of SD modelling in this particular situation was that detailed and accurate data on the water supply system (e.g. the evolution in water demand over time and variations in the water treatment pumping capacity) were not prerequisite to modelling. Instead, stakeholders contributed a deep knowledge of system design and experienced behaviour over time, which were captured within the model as operations (including decision rules and the use of information). This showed the importance of operational thinking in the way in which SD modelling was deployed in the case study (Olaya 2015).

The Greater Kirkwood Water Supply (*GKWS*) model explored how water outages have a differential impact (in that all areas of the region do not run dry at the same time). Figure 11.2 demonstrates the relative time periods that the different residential zones are without water, over a one-year simulation period. The reasons for this are detailed in Clifford-Holmes (2015) and D'Hont (2013). What is important to note here is that zone 1 is still primarily inhabited by white residents, who are comparatively wealthier than the poorer (predominantly black) communities residing in zones 2 to 5. The safety mechanisms in the technical design of the pumps, together with the nature of the gravity-feed system to Kirkwood town, collectively result in zone 1 being the last area to be cut-off, and the first area to receive water. Municipal residents living in zones 2 to 5 understandably complained that this aspect of system behaviour is inherently unjust and discriminatory, both along class and racial lines (which is especially problematic given the historical development of the town and the politics of the country under apartheid, resulting in the preferential supply of potable water to zone 1 by design). The *GKWS* model illustrated the inequitable supply system by simulating the 'time without water' across the different zones. In Figure 12.2, for example, zones 4 and 5 (line 3) are shown to lack sufficient access to potable water for more than 80% of the year. The *GKWS* model usefully demonstrated that the underlying cause of the experience of differentiated service delivery lay more in the physical characteristics of the infrastructural design than in the operational choices made by the municipal employees managing the infrastructure. Apart from the municipal engineering staff, this represented a new insight for all stakeholders and was demonstrative of the objectives of the modelling approach (which focused on systemic exploration rather than blaming individuals or institutions).

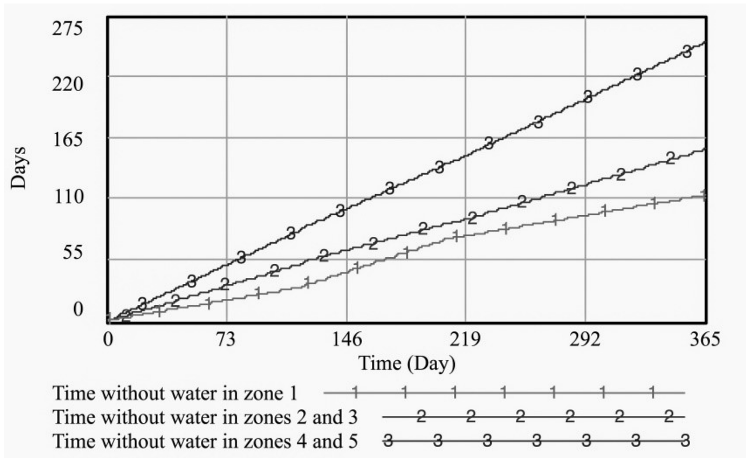

Figure 11.4 Simulation output from the Greater Kirkwood Water Supply (*GKWS*) model illustrating the time without potable water, differentiated across supply zones 1, 2 and 3, and 4 and 5. See D'Hont (2013) and Clifford-Holmes (2015) for details.

Officials from the municipality and the L-WUA involved in the *GKWS* modelling process acknowledged that infrastructure capacity issues were exacerbated by increasing water demand in the area. However, these demand dynamics were less understood and even more controversial than the supply-side dynamics. Hence, exploring the determinants of the rising demand for potable water was central to the third model, which is detailed in Clifford-Holmes et al. (2014). This third model, called the 'Kirkwood Water Demand' model (*K-DEM*), modelled the transition from households receiving basic levels of water services to those same households becoming connected to the municipal networks for water supply and waterborne sanitation. The demographic impact of this transition is visible in Figure 11.3(a), which shows that the population living in unconnected households began declining from 2006, as the population living in connected households sharply increased (resulting in a net increase in the total water demand). But whilst this dynamic was modelled in *K-DEM* at the structural level, the socio-political dynamics affecting this structure were not. One of the most important of these dynamics is driven by the way in which municipal councillors (who are politically-elected officials) respond to their constituencies' demands. A senior technical official in the SRVM (interviewed in Clifford-Holmes 2015, p. 269) described this as follows:

> Our department has been pressured by councillors to get houses up – even without the necessary infrastructural development to service these houses. Then, when we [the technical division] cannot serve the houses, we are blamed for it.

A secondary consequence of this driving demand for potable water is that water conservation and water demand management policies are politically unpopular and therefore operationally difficult to implement (despite being technically feasible). The *K-DEM* model was used as part of the action research process that engaged national and regional water authorities, in addition to municipal councillors and technical officials, around these issues. The factors pertaining to household water demand were discussed and model outputs from the *K-DEM* model were compared with engineering assessments and projections over the course of a planning workshop held in the SRVM in early 2014 (described in Clifford-Holmes 2015). This planning workshop, along with the associated reports and funding proposals, provided the opportunity to validate the dynamics explored in the *K-DEM* model. However, the process of interacting with the stakeholder groups highlighted what the *K-DEM* and *GKWS* models both failed to capture, namely, why the SRVM could neither provide adequate quantities of potable water nor effectively manage water demand in the Greater Kirkwood region, and what the different stakeholders could do about these management challenges. The fourth modelling exercise was undertaken to explore the latter issues and did so by synthetically drawing on the earlier modelling work in a process of methodological hybridisation (the results of which are described below).

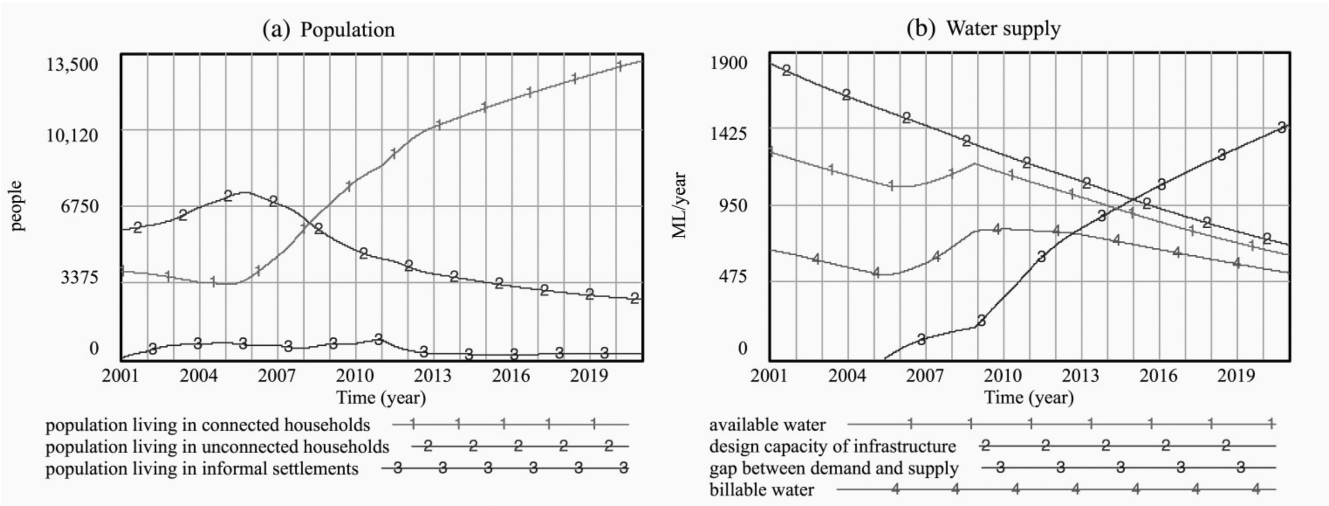

Figure 11.5 The left-hand graph (a) displays the simulated population dynamics in the Greater Kirkwood region. The right-hand graph (b) displays the simulated water supply and the quantity of 'billable water' in relation to the gap between demand and supply. See Clifford-Holmes et al. (2015) for full model.

Six interlinked 'modes of failure' were identified through the fourth modelling exercise, which are summarised in Clifford-Holmes et al. (2015: 1) as:

> 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.

The CLD in Figure 11.4 provides a 'dynamic hypothesis' of how these interlinked modes were explored in the 'modes of failure' (*MoF*) model. When the SRVM is unable to increase capacity through constructing new infrastructure, then an alternative way in which it can reduce the demand-supply gap 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 demand and supply (**B2: effect of infra. [infrastructure] overuse on supply**). The short-term dividend of this policy is visible in the simulations of the *MoF* model. In Figure 11.3(b), the gap between demand and supply begins to grow in mid-2005 (line 3), as the design capacity of municipal water supply infrastructure continues to decrease (line 2). In order to address this gap, the municipality responds by starting to over-extend infrastructure, which increases the 'available water' (line 1) between 2006 and late-2009. Given that more houses were connected to the municipal networks for water and sanitation in this period, the proportion of the 'available water' from which the municipality could earn revenue (i.e. 'billable water' in line 4) also increased. However, 'Water revenue' is determined by the proportion of billable water for which the municipality actually receives payment ('% cost recovery' in Figure 11.4). Similarly, the 'Revenue dedicated to maintenance' is subject to the proportion of the 'Water revenue' that is reserved for this purpose ('% revenue ring-fenced'). When little to no water revenue is ring-fenced, the municipality can perform no maintenance, which results in water losses and the obsolescence rate increasing, which reduces the water that can be delivered and, in turn, decreases the quantity of billable water.

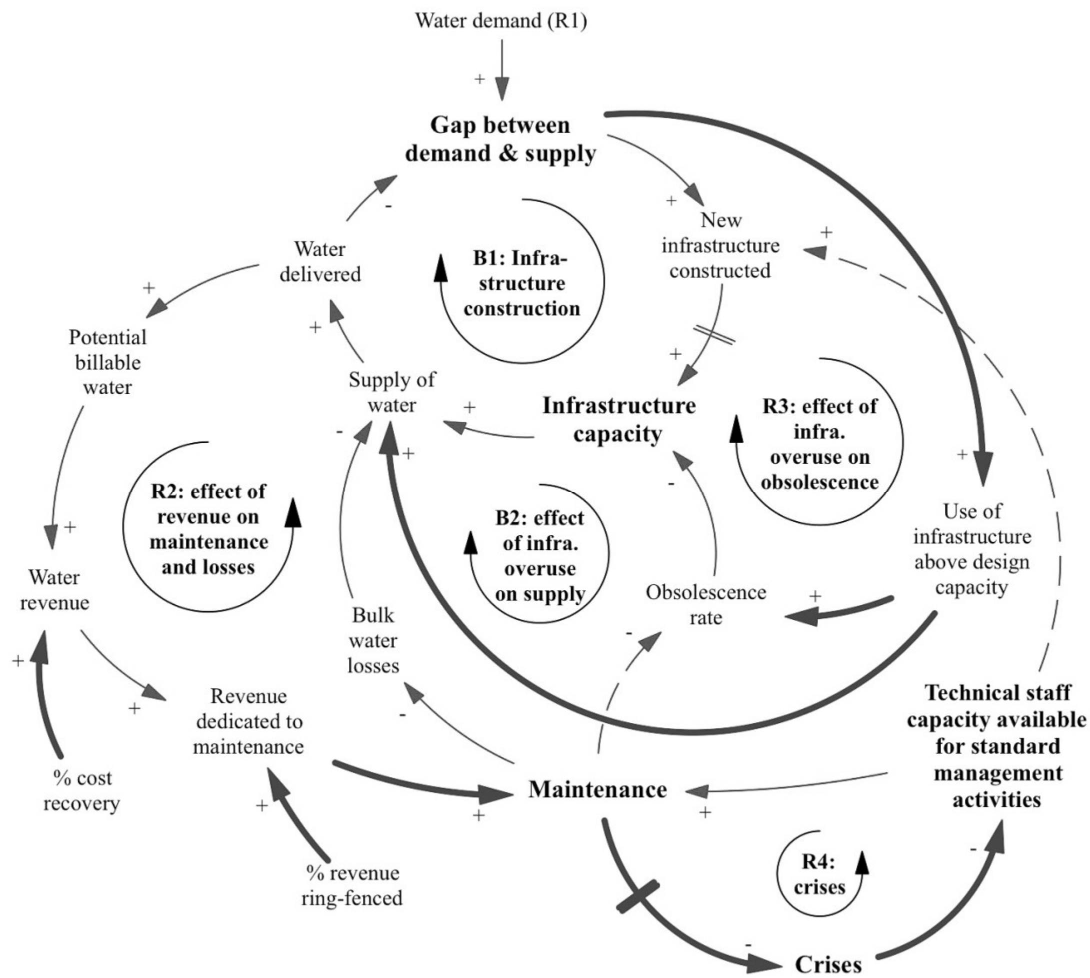

Figure 11.6 Expanded causal loop diagram showing an additional three feedback loops (B2; R3; and R4) that build on Figure 11.1. The emboldened arrows show the causal relations between the additional variables, with the two arrows dashed for the sake of clarity where the emboldened arrows overlap with other arrows. Adapted from Clifford-Holmes et al. (2015, p. 6).

Maintenance is particularly required when the municipality over-extends water supply infrastructure (given that the longer this infrastructure operates above its design capacity, the quicker it obsolesces, requiring refurbishment and replacement earlier than planned, which has a reinforcing feedback effect (**R3: effect of infra. [infrastructure] overuse on obsolescence**). As noted in Figure 11.1, maintenance is also contingent on technical staff capacity. Over the course of the intervention processes in the SRVM between 2011 and 2012, a municipal technical official argued that 'currently the status of this municipality is that we are running after the emergencies and not planning' (interviewed in Clifford-Holmes 2015, p. 186). This 'fire-fighting' response of officials reduces their capacity 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 management activities. A reduction in these activities influences maintenance 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** in Figure 11.4) became the primary endogenous driver of municipal crises explored in the *MoF* model.

The effects of these reinforcing crises were demonstrated in the dramatic events of September 2014, when municipal offices and infrastructure in the Kirkwood region were burned to the ground by protestors. The media reported several reasons for the protests, including 'water cuts that had lasted for about three weeks' (SAPA 2014, p. 1). The timing of these protests presented both challenges and opportunities to the SANPAD action research project. Work had begun on the *MoF* model in January 2014 (see Table 11.1), with validation workshops and meetings planned for the same period in which the protests occurred. The timing placed constraints on the ways in which the *MoF* model could be used in multi-stakeholder settings in the SRVM (in the traditional manner of 'group model building' (Vennix 1999)); on the other hand, the protests provided the opportunity to use the *MoF* modelling initiative to clarify the socio-technical problem and to use SD as a tool to effectively communicate the causes of local water services system failure to different audiences (which is closer to the approach advocated in 'mediated modelling' (van den Belt 2004). Model diagrams and model-related issues were used to pose questions and engage different stakeholders in conversation following the September 2014 protests. The six modes of failure derived through this modelling approach particularly resonated with the participants of the SANPAD project from the municipal technical division. This was demonstrated when a modeller co-presented an adapted version of Figure 11.4 with a senior municipal official in November 2014. The setting was a national-level 'Water Dialogue' initiated by the South African Water Research Commission and attended by senior representatives of several national government departments (described in Clifford-Holmes 2015). Following this presentation, the municipal official co-authored a paper on the *MoF* model with SANPAD researchers (Clifford-Holmes et al. 2015), using this opportunity to review the quantitative simulation model underpinning Figure 11.4.

In summary, all three models explored the effects of practices that met short-term goals in ways that had intermediate- and long-term (negative) implications. For example, the rapid connection of households to the municipal reticulation network (as explored in the *K-DEM* model) and the over-extending of water supply infrastructure above its design capacity (as explored in the *MoF* model) are practices that respond to immediate demands in ways that require greater levels of activity in the future. This short-term response is a well-known systems trap, which is referred to within the SD field as a 'better-before-worse' response (see Lyneis & Sterman 2016). In the SRVM case study, the short-term practices that were operationally caught within the SD models were contextualised with further institutional analysis. For example, technical officials are pressured by elected (i.e. political) officials to connect households as quickly as possible (as noted with *K-DEM*). A South African infrastructural analyst has accounted for this pressure in terms of new housing developments attracting 'vast amounts of attention and support at the highest level… plans are put in place, resources are made available and importantly the completed projects present "ribbon cutting opportunities"' (Infrastructure Dialogues 2013, p. 10). Many components of the bulk water supply systems that are required to support these new housing developments are underground and 'out of sight' (Rehan et al. 2014). As such, they offer fewer 'ribbon cutting opportunities' for political elites and therefore typically receive less attention *unless* crises occur. By the time such crises do occur, the damaging conditions that have created many of the crises are already institutionalised (Repenning & Sterman 2001). An emerging theme of the modelling process reported on here was 'the characterisation of government actors as 'fire-fighters' who reactively respond to crises and who are not in control of their own time' (Clifford-Holmes 2015, p. 384). That 'stamping out spot fires does not stop a major bushfire' (Haslett 2007, p. 1) is hardly surprising. Indeed, Simon (1996, p. 161) characterised it as a commonplace organisational phenomenon that

> … attending to the needs of the moment – putting out fires – takes precedence over attending to the needs for new capital investment or new knowledge. The more crowded the total agenda and the more frequently emergencies arise, the more likely it is that the middle-range and long-range decisions will be neglected.

An institutional response to the fire-fighting tendency is to create planning and management groups that are immune to the day-to-day pressures, which provide regulatory oversight and the space to consider longer-term issues along with the capacity to plan and act on these considerations. The lack of such institutional separation between operations, regulations and planning was evident in two key places in the SRVM: in the water services managed by the SRVM itself; and in the water supply arrangement between the SRVM and its bulk water supplier (Clifford-Holmes et al. 2016).

The following section discusses the defining characteristics of the 'modelling in the muddled middle' approach, with reference to the results described in this section and with reference to the emerging theory and practice of social systems engineering.

11.6 Discussion

The value of modelling within transdisciplinary research is broadly acknowledged, for example, as a means of understanding and responding to complex real-world problems, synthesising knowledge, and providing potential decision-support (Badham 2010). Furthermore, as Voinov and Bousquet (2010) demonstrate in their authoritative review of modelling with stakeholders, a plethora of approaches exist for interacting with stakeholders at different points of the modelling process, and employing different techniques and tools. System dynamics (SD) modelling was found to be particularly relevant in the SRVM case for three reasons. Firstly, SD characterises systems by time and time evolution, which allows for the artificial representation of a given system using differential equations (Luenberger 1979). This temporal rendering of problem dynamics was useful given the frequent focus on short-term actions carrying secondary consequences in the long-term (as noted in the results section above). Secondly, SD modelling – as conceptually underpinned and methodologically employed in this study – contains many social dimensions (see section 11.3), which were especially pertinent given the second-order water scarcity in the SRVM (as introduced in section 11.2). Thirdly, SD was selected because it is one of the few modelling approaches that allows for exploring actual practices and experiences of stakeholders in applied settings (Maani & Cavana 2007). Focusing on 'actual practices' supported a grounded analysis of water management challenges in the SRVM, which featured 'actual people who could do or who are doing things that affect other people' (Agnew 2011, p. 469). As Olaya (2015, p.211) notes, SD modelling is a nonempirical approach in that it does not require strict numerical validation to be useful; furthermore SD modelling encourages researchers 'to go and ask the [relevant] human beings… how they do what they do' (*ibid*).

The four SD models, which were developed through the approach described in this chapter, were used to explore scarcity in different ways. In the process of developing the *GKWS* model, for example, stakeholders were asked for the physical measurements of a supplementary storage canal in the water supply scheme. Stakeholders responded both with different measurements and with differing opinions on the perceived relevance (or irrelevance) of this canal as an additional raw water storage facility. Asking for the measurements of the canal (as parameter data for the *GKWS* model) created an opportunity to discuss policy options with different stakeholder groups, without personalising or blaming the operational issues on any one actor. The *GKWS* model was therefore built from a functionalist perspective that a model could represent 'the real world' (in this case, a specific water supply scheme). The *MoF* model, on the other hand, was consciously employed in discussion with stakeholders as a 'socially-constructed artefact' that was used to facilitate what Howick and Eden (2010) call 'strategic conversations'. In these two respects, the modelling approach described here is similar to that of group model-building (GMB), which conceives of models of social systems as carrying dual identities stemming from functionalist and constructivist perspectives (see Andersen et al. 2007). Where the modelling approach differed to GMB was in the way in which the four SD models were *not* constructed in groups. Instead of bringing a heterogeneous group together and striving to build consensus amongst its members, modellers went from group to group, with different stakeholders interacting at different points in the process. The SD models were then used to support the action research process as 'boundary objects' (Star & Griesemer 1989), rather than the models themselves being the objects of focus. As described in the above sections, four small SD models were developed through this action research process, rather than one large model being developed at the end of the process. The SRVM case provided further evidence in support of Ford's (2009, p. 305) assertion that developing a 'portfolio of [small] models' frequently offers the opportunity to learn more 'than a single, all-encompassing model', reflecting the fact that participatory modelling is more often about 'the process rather than the product' (Voinov & Bousquet 2010, p. 1272).

The literature review in section 11.3 noted that ethnographic tools and perspectives focus on the subjective interpretations of the world that individual social actors employ. The hybrid approach of SD modelling and ethnographic analysis, as employed in this study, used the ethnographic (agency-based) perspectives as a counter-balance to the systems (structure-based) perspectives that SD is frequently accused of privileging. The hybrid approach sought to explore how agents interpreted the problems they faced and found ways of working in the 'muddled middle' between formal institutional structures and informal, practice-based realms. The interpretive perspective reflects a narrative approach to social systems, which conceives of complexity as an attribute of those agents who interact with social systems, rather than solely being an attribute of systems themselves (see Tsoukas & Hatch 2001). The methodological hybridisation of systems, ethnographic, and institutional analyses evolved iteratively through the case study. The key benefits of the hybrid approach are consistent with other analyses of the ‘added value’ of combined approaches. As Horlick-Jones and Rosenhead (2007, p. 599) note with reference to problem structuring methods, hybrid approaches of ethnographic and systems perspectives provide ‘insights into the practical worlds inhabited by the participants and the nature of the problems they [face]’; furthermore, these approaches enable researchers to develop perspectives on problematic situations that transcend ‘the subjective understanding of any one actor’ (*ibid.*, p. 595).

Whilst this case study was undertaken, the South African national government acknowledged that the failure of local government to provide adequate water services, as dramatically demonstrated in the SRVM, partially resides in the institutional design. In 2013, revised policy positions were put forward by government in order to resolve these failures (DWA 2013). For systems thinkers, institutional failures are opportunities to ‘revise, improve, rescind, or better explain the rules’ (Meadows 2011, p. 137), yet doing so within regulated sectors (such as water management) requires broader contextual analyses of the institutions and organisations (as noted in section 11.3). The ways in which the financial components of municipal water services were modelled in the case study is illustrative. In the *MoF* model, the ‘Revenue dedicated to maintenance’ was modelled as being subject to the proportion of the ‘Water revenue’ that is reserved for this purpose (‘% revenue ring-fenced’). Whilst the *MoF* model was being validated in interaction with municipal stakeholders in late-2014, the South African Minister for Water and Sanitation announced that legislation would be introduced requiring municipalities to reserve a minimum of 7% of their total budgets for the maintenance and management of infrastructure (infrastructurene.ws 2014). The broader institutional analysis provided the means to understand the socio-political contexts of these legislative changes (see Clifford-Holmes et al. 2016). These understandings were then used for communicating the simple scenarios explored within the *MoF* model, such as the impact of adjusting the parameter of the ‘% revenue ring-fenced’ on the variable ‘supply of water’ (see Figure 11.4). The choice to *not* directly model the changing institutional context was motivated by the principle of keeping models ‘requisitely simple’ (i.e. by only including operational detail that enables a given model to be useful (Stirzaker et al. 2010).

Within the hybrid approach described in this chapter, modelling is positioned as an activity undertaken in the ‘muddled middle’, which is conceived as the space between the clean lines of policy design and the messy operational reality of implementation. In the case study, modellers exercised judgement about what to model, where, and with which stakeholders, in addition to being flexible with how stakeholders were involved in the model-building and validation processes. This approach has subsequently been employed elsewhere in South Africa as part of another project, which is larger both in scope and in geographic scale (see Clifford-Holmes et al. 2016). The commonalities between the SRVM case and this larger case include transdisciplinary action research, methodological hybridisation, and a deep interest in social systems design and transformation (*ibid*). The modelling approach is held to be particularly relevant for exploring controversial and complex case studies that offer representative and extreme examples of systemic dysfunction, where policy-level analytical objectives co-exist with action research imperatives of employing tools and methods to understand (and where possible, address) stakeholders’ issues of concern.

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