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Chapter 6

Using System Dynamics Modelling in South African Water Management and Planning

Jai K Clifford Holmes[a], Jill H Slinger[b], Carolyn G Palmer[c]

Abstract

The effective governance and management of water has many environmental, socio-political, economic and technical dimensions, which frequently interweave in a 'wicked web' that presents significant challenges to planners, policy makers and networks of citizens. This chapter evaluates the use of system dynamics modelling (SDM) as a tool for policy analysis and planning, with emphasis on the management and governance of water in an African context. The strengths and limitations of SDM are related to the characteristic challenges of integrated water management and participatory water governance. A conceptual framework is posited for distinguishing between diverse motivations for undertaking modelling for developmental planning. The framework is used for reflecting on a selection of South African cases between 1980 and 2016. Three of these case studies are then described and discussed, emphasising how SDM was variously used to address some of the key challenges facing planning at different scales of water management. The outcomes of SDM-based interventions are discussed, including examples of models being used to inform the design of more equitable operational policies for water releases; the use of SDM to create shared focal points amongst stakeholder groups; modelling as an integrative activity that can synthesise knowledge drawn from different specialists and fields; and the appropriateness of SDM in the data-scarce and politically charged contexts of African water and coastal management.

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6.1 Introduction

The effective governance and management of water has many environmental, socio-political, economic and technical dimensions, which frequently interweave in a 'wicked web' that presents significant challenges to planners, policy makers and networks of citizens. This chapter evaluates the use of system dynamics modelling (SDM) as a tool for policy analysis and planning, with emphasis on the management and governance of water in an African context. The chapter begins by summarising the arguments on why system dynamics (SD) offers an appropriate toolkit and conceptual framing for engaging 'wicked webs' of water issues, as reflected in international literature reviews on this subject and as demonstrated in a selection of South African cases between the 1980s and 2016.

The focus of the chapter then turns to demonstrating the use of SDM in three diverse cases. In the first case, SDM supported analysis on the timing of water releases above the Pongola floodplains as part of a multi-disciplinary project. This study, undertaken in the mid-1980s, represents the first use of SDM to support social-ecological systems-based decision making on water systems in South Africa. In the second case, SDM was employed for exploring the interlinked 'modes of failure' of local government in South Africa (between 2012 and 2014), including the simultaneous underinvestment in, and over-extension of, water supply infrastructure, and the effects of municipal staff shortages, emergencies, and overcommitment on technical activities. The third, most contemporary case describes an ongoing project in which SDM is being used to help stakeholders think through different scenarios of change (including climate change) in a catchment with diverse activities and different interest groups. The chapter discusses the strengths and limitations of SDM, with reference to the literature review and the three water management cases, and assesses the broader implications for using SDM in similar ways outside of South Africa.

6.2 Assessing the relevance of system dynamics to water

Considering the particular characteristics of water provides an appropriate point of departure for assessing the relevance of SDM to water management and planning. The following characteristics of water are summarised from similar lists in Savenije[1] and Sampford:[2]

- Like land, water is a scarce resource with quantities of water unequally distributed across space.
- Water is constantly in a state of flux, varying over time rather than being available as a stock (as air and land are).
- Available water is subject to a series of hydrological processes that are interdependent and interconnected.
- The same water can be re-used within a single cycle.
- Water is bulky: transporting water across catchments, and from where water naturally flows to where it is required, is costly and resource-intensive.

Proponents of integrated water resources management (IWRM)[3] draw from such lists in arguing for the necessity of multidisciplinary, multi-sectoral and multi-stakeholder integration in the planning, management and decision making around water (e.g. Lenton and Muller,[4] and Thomas and Durham[5]). Adopting a systems perspective incorporates many of these imperatives. Systems thinking is based on a holistic worldview that emphasises interrelationships rather than parts, and patterns of behaviour over time, rather than static snapshots. This holistic worldview can be defined as a systems thinking paradigm (as described in Box 6.1 below).

Box 6.1 Descriptions of a 'systems thinking paradigm'

Forest thinking: striving to see the 'big picture' and how the component parts relate and interact;
Operational thinking: understanding the 'physics' of operations and how things work and affect each other;
Dynamic thinking: recognising that the world is not static and that things change constantly;
Closed-loop thinking: recognising that cause and effect are not linear, and that often the end (effect) can influence the means (cause/s).

Source: Drawn from Richmond.[6]

Applied to water, systems thinking moves away from 'looking at isolated situations and their causes, and starts to look at [the water system] as a system made up of interacting parts'.[7] By doing so, a systems approach aims to mitigate the shortcomings of linear analyses that emphasise a certain relation between a cause and a given effect. In its place, proponents of a systems approach are interested in feedbacks, and the behaviour of a system over time and under different conditions. The characterisation of dynamic systems by time and time evolution allows for representing a given system mathematically, using differential equations (Luenberger 1979).[8] As Musango[9] points out, 'it is these equations that provide the structure for representing time linkages among variables'.

Given the nature of water, summarised in the above list of characteristics, hydrological modelling typically incorporates both spatial and temporal complexity, with geographic information systems (GIS) used to model the movement of water across landscapes.[10] In contrast, traditional system dynamics modelling does not account for spatial dynamics, electing instead to focus on dynamic complexity. However, the past two decades have seen the development of a number of hybrid methodological approaches that seek to incorporate spatial complexity into system dynamics models. These include integrated toolkits, such as the one developed by Sandia National Laboratories;[11] the 'Spatial Modeling Environment' (SME) and modelling platforms, such as Simile;[12] and the Multi-scale Integrated Modelling of Ecosystem Services (MIMES).[13] In order to assess how SDM has been applied in developmental planning and management in the South African water sector, the following section posits a conceptual framework for categorising the purposes of undertaking modelling.

6.3 Conceptual framework

Models are widely used in the water sector.[14] In their most obvious forms, models provide predictions and forecasts for planning and management purposes. The ramifications of these model predictions range from the personal and the mundane (e.g. failing to pack an umbrella and finding oneself caught outside in a downpour) through to the life (and livelihood) threatening (e.g. dam managers releasing water downstream, trading-off between flood protection and water for irrigation and people). In these cases, the more accurate the predictions, the better everyone can manage.

The accuracy of predictions raises the thorny issue of trust in a model. By definition, a model is a simplification of reality that is at once imperfect and incomplete (hence the statistician George Box's famous statement that, 'essentially, all models are wrong, but some are useful').[15] What makes a model useful is less the inclusion of all the possible information, and more the inclusion of what is adjudged to be the most relevant information. As John Sterman (another famous SD modeller) put it, whilst a map is a model of a territory, it is not the territory itself, and indeed, 'a map as detailed as the territory would be of no use (as well as being hard to fold)'.[16] Stirzaker et al.[17] reason that even if it was technically possible, including all relevant information in a model would not help to solve the kind of complex problems that the water sector faces:

> If we have a model which is just as complex as the system it models, it will be just as difficult to understand as the system itself. We will also not be able to judge if the model actually tracks the system correctly in time and space. It is often therefore better to have a simpler model which we understand, and understand the limitations of, than a complex one we do not understand.[18]

The above suggests that there are different reasons for undertaking modelling in addition to prediction and forecasting. Some alternative motivations for modelling are suggested in Box 6.2, all of which are relevant to the water sector.

Historically, modelling in the water sector has been undertaken by experts for scientific purposes and for engineering and design purposes. In the past two decades, there has been a move to incorporate others into modelling processes so that they are not solely expert-driven. In their paper *Participatory model construction and model use in natural resource management: A framework for reflection*, Bots and Van Daalen[20] (2008) argue that the analysts who design a modelling exercise should deliberate on *whom* to involve *when*, as well as on *how* to involve them. The authors propose a framework to assist in the early, design stages of a modelling exercise.

Deciding on whom to involve when, as well as on how to involve them, should be subject to the intended purpose of the modelling exercise. Drawing upon the work of Bots and Van Daalen,[21] we distinguish four primary motivations for modelling (see Figure 6.1). Modelling can be undertaken in order to research and analyse a given problem; to design and recommend solutions or plans; to clarify arguments

Box 6.2 Alternative modelling goals to prediction and frecast

1. To explain phenomena (as distinct from predicting);
2. To guide data collection;
3. To illuminate core dynamics;
4. To discover new questions;
5. To promote a scientific habit of mind;
6. To illuminate core uncertainties;
7. To offer crisis options in near-real time;
8. To demonstrate trade-offs;
9. To challenge the robustness of prevailing theory;
10. To expose prevailing wisdom as incompatible with available data;
11. To discipline the policy dialogue;
12. To educate the general public;
13. To train practitioners;
14. To reveal the apparently simple to be complex; and
15. To reveal the apparently complex to be simple.

Source: Drawn from Epstein.[19]

and values between different interest groups; or to mediate and broker (if the different interest groups are competing or in conflict). Rather than these diverse objectives being seen as discrete, Figure 6.1 represents them as existing along four continua.

Continuum 1 represents the traditional academic and consulting roles, where modelling is aimed at leading to policy design and recommendations. On the one pole is research and analysis, expressing the traditional scientific aims of 'understanding the world that is'. The positing of a design or the making of recommendations for a specific client lies at the other end of the continuum, where modellers contribute towards 'designing systems that do not currently exist, but that we want to exist'.[22]

Continuum 2 (between research and 'clarify arguments and values') is explicitly about different types of understanding: at one pole, the attempt to understand phenomena and interactions (typically in the biophysical realm); at the other, the attempt to understand, explore and represent the social realm, querying what is important to which stakeholders (i.e. values) and why (i.e. arguments).

Continuum 3 represents democracy-in-action, where attempts to clarify arguments and values (using models) segue into activism, advocacy and action research, explicitly aimed at mediating between conflicting stakeholders and brokering agreements.

Finally, continuum 4 reflects levels of interventions, from the safe to the risky. Situations in which modellers are solicited to design and provide recommendations in a particular situation (typically where the client is a single problem-holder) are safer because the modelling exercise is undertaken to address an established (and recognised) need. Activism, advocacy and action research lies at the other, riskier end of the continuum, where modelling is undertaken in situations with multiple problem holders, but without any one problem holder being the soliciting client. At this end of the spectrum, careful facilitation between stakeholders is a crucial component of the modelling exercise. Scenario thinking is important here. Stakeholders can be involved in collaboratively developing and defining scenarios and the S.M.A.R.T. response strategy for each scenario (where S.M.A.R.T. refers to strategies that are **S**pecific, **M**easurable, **A**chievable/**A**greed upon, **R**elevant, and **T**ime/Cost bound). In this respect, simulation models can be particularly useful for helping to generate these scenarios and for facilitating dialogues between decision makers.[23]

The conceptual framing summarised in Figure 6.1 provides the scaffolding for distinguishing between the diverse motivations that modellers (as consultants, researchers or activists) may have for modelling in developmental contexts. In the following section, this framework is used for structuring a brief literature review of modelling in the water sector.

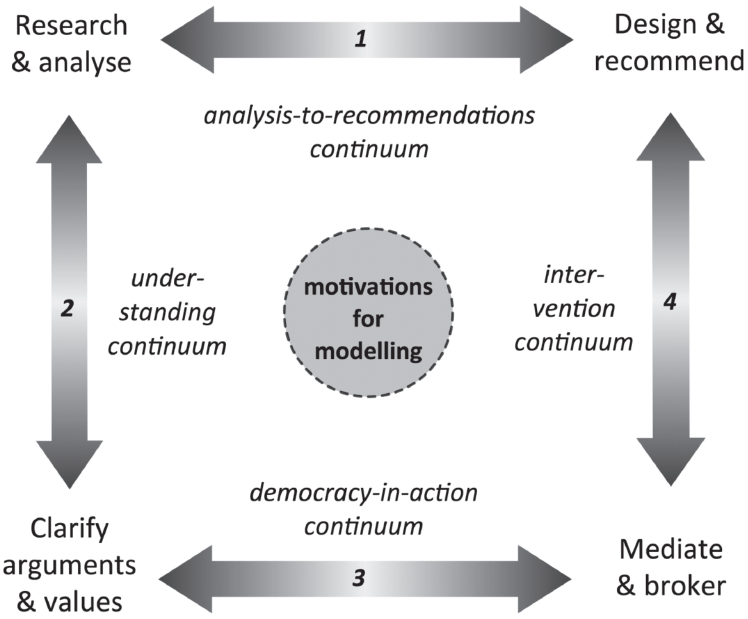

Figure 6.1 Conceptual framework for distinguishing between diverse motivations for undertaking modelling for developmental planning

6.4 Literature review

Considered globally, the themes that have traditionally garnered the greatest attention of SD practitioners in the water sector are those of regional planning and river basin management, and flooding and irrigation.[24,25] 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;[26] urban drinking water supply;[27] and urban wastewater management[28]). The majority of these modelling efforts were expert-driven (and could therefore be situated along Continuum 1 of Figure 6.1). But an increasing amount of attention has been paid in the last two decades towards developing approaches that engage stakeholders in SDM. The most-documented approach is 'group model-building',[29,30] which aims to build or come to a group understanding of a complex problem. Other examples in the water sector of stakeholder-engaged SDM have been termed 'cooperative modelling';[31,32] 'mediated modelling';[33] and 'participatory model building'.[34,35,36,37] The modelling efforts grouped under these approaches can be variously situated along Continua 2, 3, and 4, but distinguishing where exactly lies beyond the scope of this chapter.

From a more regional perspective, a systematic review of scientific literature published between 2003 and 2014 shows that SDM is on the increase throughout 11 countries in Southern Africa.[38] The latter review identified that water frequently crosses three of the themes used as categories by the international System Dynamics Society (environment, resources, and public policy). The breadth of ways in which SD has been used in the water sector mirrors the characteristics of water and its cross-cutting thematic nature (as introduced in the earlier section on the relevance of SD to the sector). Turning to South Africa, applications of SD in the water sector can predominantly be situated along Continuum 1. These applications include:

- Timing of flood releases from the Pongola Dam;[39]
- Analysing combined flood release and mouth breaching strategies to enhance the social-ecological health of an estuary and associated coastal community;[40]
- Explorations of the socio-technical challenges faced by small, rural municipalities as they attempt to provide water services in the face of growing demand;[41],[42] and
- A study of the South African 'Green Economy', funded by the United Nations Environmental Programme (UNEP), in which water featured prominently.[43],[44]

An example of a recent application of SD in the South African water sector that can be positioned on both continua 2 and 3 is Waas et al.,[45] where Waas and colleagues developed a model as a 'boundary object' and used it to generate discussion and to clarify arguments. This is in line with recent SD research that employs models as transformable objects that are developed and used in group contexts.[46] An application of SD that can also be positioned along Continuum 3 is work that was undertaken into the 'modes of failures' of South African local government,[47,48] in which the modelling process was used partly to mediate between conflicting actors and to represent diverse perspectives. This case is discussed along with two others in the remainder of this chapter, which highlights a number of different ways in which SD modelling has been applied in water management and planning case studies in the last three decades (1986–2016).

6.5 Country and case studies overview

The Republic of South Africa (RSA) is a water-stressed country, with a mean average annual rainfall of almost half of the global average (450 mm compared to a global average of 860 mm).[49] Climatic conditions vary across the country: Durban, in the KwaZulu-Natal province, where the first case study is located, has an average annual rainfall in excess of 1 000 mm, while '65% of the country has an annual rainfall of less than 500 mm and 21% receives less than 200 mm'.[50] The arid and semi-arid environment of much of the country results in a low conversion of rainfall (Mean Annual Precipitation – MAP) to usable runoff (Mean Annual Runoff – MAR). In the Orange and Limpopo river systems (which provide water in the second and third cases in this chapter), the MAP:MAR conversion rate is only 5.1 per cent (meaning that 94.9 per cent of the rainfall is lost as evaporation shortly after rainfall events[51]). Storage of water in reservoirs therefore forms an important part of managing RSA's water resources. Ensuring security of supply for key water users must be balanced with maintaining ecological functioning (which is fundamental to South African water law), along with the equitable provision of water to competing users.

The socio-political and institutional context of South Africa's water landscape is equally varied. This context includes:

- A history of segregation in the form of institutionalised apartheid;
- The effects of this segregation continuing to be made evident in South Africa's high levels of both poverty and inequality;
- A post-apartheid water management framework that embodies the ambitions of integrated water resource management (IWRM);
- The ground-breaking recognition of the freshwater needs of marine and coastal water bodies – lagoons and estuaries – and their subsequent inclusion in the freshwater law;[52] and
- Developmental planning being enshrined across all the three spheres of government in the RSA.[53],[54],[55]

Implementing the above-mentioned ambitions has not been a straightforward journey for the RSA, with many operational manifestations of institutional dysfunction evident and continual challenges in addressing 'who gets what water, when, and how'.[56]

The three case studies in this chapter discuss the use of SDM for approaching various challenges of developmental planning. The case studies are located in rela-

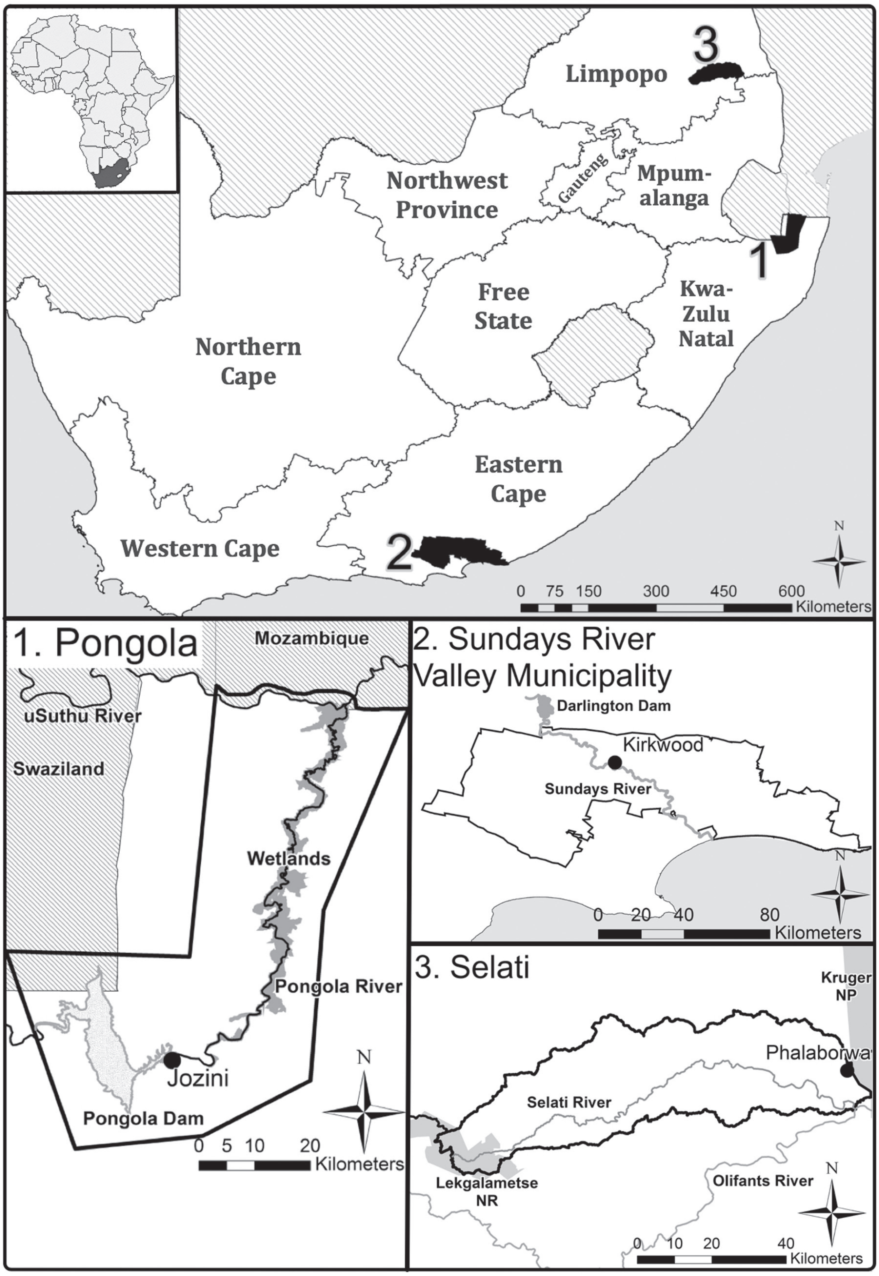

Figure 6.2 Composite map of the three case studies discussed in this chapter, located at the continental and national scale. In the detail on the third case study (the Selati), portions of two nature reserves are shown, namely the Lekgalametse Nature Reserve (NR) and a very small portion of Kruger National Park (Kruger NP).

tion to one another in the composite map in Figure 6.2. The top pane of the figure shows the location of the three cases studies within the nine provinces in the RSA. Case 1, in the KwaZulu-Natal province, describes how SDM supported analysis on the timing of water releases above the Pongola floodplains. Case 2, situated in the Eastern Cape province, describes SDM as it was used to explore the 'modes of failure' of local government in providing drinking water services to residents in the Sundays River Valley Municipality. Finally, case 3 describes an in-progress project situated in the Limpopo province, where SDM is being used to help stakeholders think through different scenarios of change in a catchment characterised by diverse activities and different interest groups. In the following three sections, the case studies are described in terms of the problematic contexts of each project; the use of SDM within each project; and learnings and insights arising from each case.

6.6 Case study 1 – The Pongola floodplain

The Pongola River floodplain, which covers an area of approximately 13 000 hectares, is situated on the coastal plain of northern KwaZulu-Natal (see Figure 6.2). The extent of the floodplain, its importance to the livelihood of the local population, and the high biological diversity made it an object of national scientific interest and policy relevance in the 1980s. The Inland Water Ecosystems National Programme for Environmental Sciences funded a ground-breaking interdisciplinary study on the Pongola floodplain in which environmental scientists, anthropologists and engineers sought to understand human–environment interactions so as to manage water releases to the floodplain from the upstream Pongola Dam more effectively.[57] The use of SDM in this programme can be situated along Continuum 1 of Figure 6.1, in that modelling was undertaken as a research exercise aimed at contributing recommendations for the release policy.

Until the development of the Pongola Dam in 1972, the floodplain comprised many shallow lakes that were periodically inundated as the Pongola River burst the narrow confines of its channel during the rainy season in the austral summer each year. This natural pattern was disturbed by the impoundment of the river and was replaced by an anthropogenically determined, reduced flooding pattern. The irrigation needs of agriculture determined the volume, timing and duration of water releases to the floodplain in the first ten years post-impoundment. These occurred in August to promote spring planting and occasionally in March to enable a second planting season. The sensitive wetland ecosystem and the livelihoods of the local inhabitants were regarded as secondary considerations in determining flooding policy. This stimulated the University of KwaZulu-Natal to undertake two SDM studies to investigate the effects of water releases from the Pongola Dam on the ecosystem and the ecosystem services traditionally derived from the Pongola floodplain by the local inhabitants.[58,59] These ecosystem services included the harvesting of fish throughout the year and the grazing of livestock on the floodplain.

Two lakes on the Pongola floodplain were selected as the two model case studies, because of the availability of empirical data and their prototypical nature – one a permanent lake, Tete Pan, and the other an ephemeral lake, Namanini Pan. Tete Pan represents an aquatic system used primarily for fishing, particularly in the dry season, when it is one of the few permanent water bodies remaining on the floodplain. Namanini Pan represents a predominantly terrestrial subsystem used extensively for the grazing of cattle on the nutrient rich meadows growing on the retreating margins of the ephemeral wetland lake. The objective was to determine the timing and duration for an annual flood release pattern beneficial to the wetland ecosystem and the services it provided to the local people.

A range of water releases were tested and the model results for the (semi-)permanent wetland lakes were validated against empirical data, including the biomass of flood-(in)dependent spawning fish; the mass of plant detritus; and cattle numbers, grazing rates and condition. Sensitivity analyses were conducted, engendering confidence in the robustness of the model outcomes as these were not sensitive to uncertainties in the input data. The flood release pattern that yielded beneficial results for Namanini pan, in terms of year-round fish yield and cattle condition, comprised a large flood in March followed by a smaller flood in November. In contrast, the flood that yielded the most beneficial results for Tete Pan, in terms of the total fish biomass of both flood-dependent and flood-independent spawning fish, comprised a large flood in February, followed by a smaller flood in December. The associated effects on the water levels in each of the water bodies are depicted in Figure 6.3, while the ecosystem response in terms of the biomass of fish in Tete Pan and the condition of the cattle for Namanini Pan are given in Figure 6.4 and Figure 6.5, respectively.

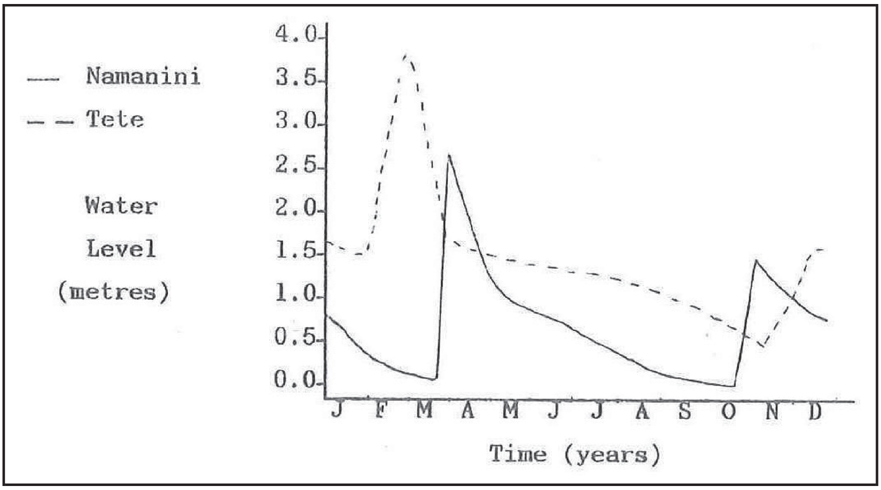

Figure 6.3 Original graphs of the variations in the water levels of Namanini Pan and Tete Pan associated with the water release patterns beneficial to their ecosystems and the ecosystem services of fish yield and pastoral grazing

Source: Reproduced from Drewes and Slinger.[60]

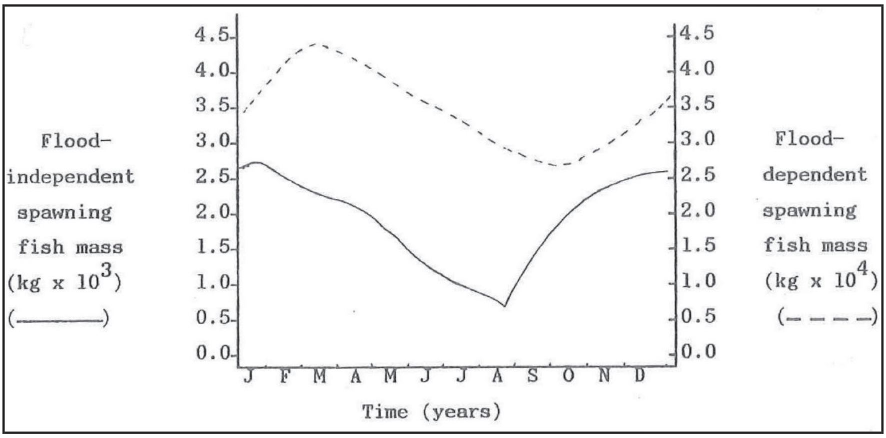

Figure 6.4 Original graphs of the variations in the biomass of flood-(in)dependent spawning fish in Tete Pan in response to a large flood in February and a smaller flood in December. The fish biomass responds to the availability of detritus over the preceding months and to the protection from predation and harvesting offered by water of sufficient depth.

Source: Reproduced from Drewes.[61]

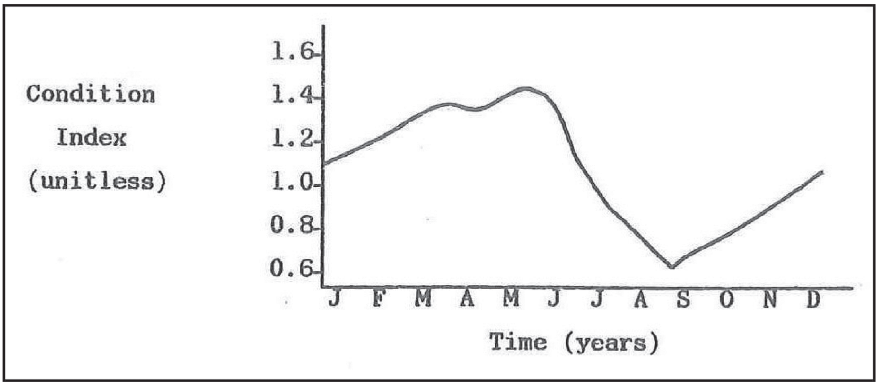

Figure 6.5 Original graphs of the variations in the condition of the cattle grazing on the meadows at Namanini Pan following a large flood in March and a smaller flood in November. The condition of the cattle represents a delayed response to the availability of sufficient fodder and its nutritional quality over the preceding months.

Source: reproduced from Slinger.[62]

In conclusion, the timing and duration of the floods beneficial to the permanent and the ephemeral wetland lakes differed somewhat from one another and deviated significantly from the August flood deemed most beneficial for agriculture. The necessity of a flood in late summer (February/March) for both the permanent and temporary wetland lakes was established, while the desirability of an early summer (November/December) water release for both the pastoral system and the aquatic system was also indicated. The insights from the system dynamics modelling studies were discussed in meetings of the wider scientific programme and were communicated to the Department of Water Affairs (the national government department responsible for flooding policy). The insights led to an adaptation of the annual water release policy for the Pongola Dam, to include more variation in the timing of the spring flood release (ranging from August to November/December), and the intention to include a biennial release in February/March. Hence, the modelling efforts served:

1. To integrate the ecosystem knowledge of botanists, zoologists and anthropologists into a coherent systems understanding;
2. To simulate the effects of different water release policies on the ecosystem and ecosystem services; and
3. To connect the outcomes to decision making on water release policies.

This study represents the first use of SD to support ecosystem-based decision making on water systems in the RSA.[63] Subsequently, systems models of coastal systems were developed and used to encourage ecosystem-based decision making in coastal management.[64] Dr Alan Ramm developed a model on the nutrient balance in estuaries and applied it to a number of small systems along the coast of KwaZulu-Natal; and Dr Jill Slinger developed an SD model of temporarily open/closed and permanently open wave-dominated estuaries and applied it to a number of estuaries on South Africa's south-eastern seaboard.[65] These estuary modelling efforts played a significant role in the development of a decision support capability for setting environmental flow requirements for estuaries[66] and were instrumental in ensuring that estuaries – traditionally regarded as marine or coastal water bodies – became included under the provisions of the new Water Law of South Africa.[67]

6.7 Case study 2 – Sundays River Valley Municipality

The effective provision of drinking water by municipalities has proven to face multiple challenges in post-apartheid RSA.[68] The Sundays River Valley Municipality (SRVM), situated in the Eastern Cape province (see Figure 6.2), offers an illustrative case of these challenges. With a relatively small population of 54 500, the SRVM is a primarily rural municipality with a number of small urban settlements interspersed between large commercial farms and nature reserves.[69] The local government authority of the SRVM is responsible for providing water services to all urban water users within its jurisdiction. Almost half of the municipal population is reliant on social grants from national government and on 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.[70] In 2010, national and provincial government departments initiated intervention processes in the SRVM, following an extended period of financial mismanagement and bankruptcy of the municipality 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 protesters and burned to the ground.[71]

An action research project funded by the South Africa Netherlands Research Programme for Alternatives in Development (SANPAD) was involved in these interventions between 2011 and 2014. The researchers employed SDM as an analytical tool and modelling approach, developing a portfolio of small models.[72] In the lead up to, and over the course of, the September 2014 protests mentioned above, a synthesis model was developed that explored the 'modes of failures' of South African local government,[73] which forms the focus of the case study as described here. This case study demonstrates the use of SDM as part of a broader intervention in which modelling (and the resulting model) was used to mediate and broker (see Figure 6.1).

Figure 6.6 displays a qualitative representation of the 'modes of failure' (MoF) model as a causal loop diagram (CLD), with the *gap between demand and supply* as the central driver. This gap increases with the *total water demand* and decreases with *water delivered*. Historically, the standard municipal response to this gap has been 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 6.6 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 – **B1: infrastructure construction**.

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. 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 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, 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**.

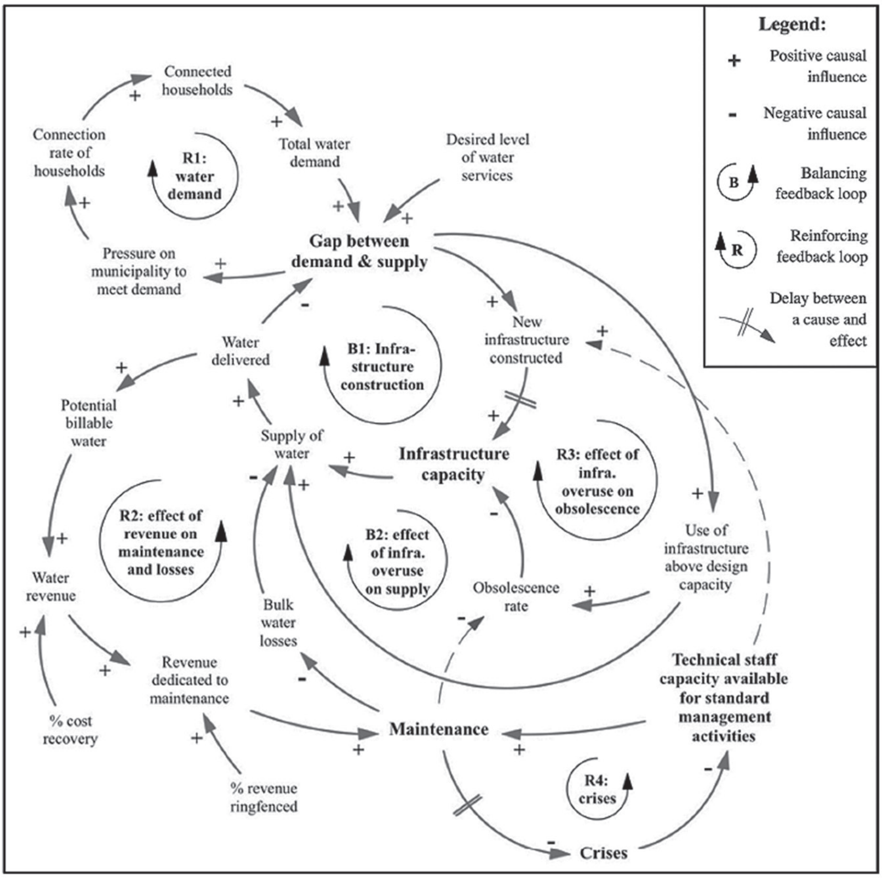

Figure 6.6 Causal loop diagram of the interconnected 'modes of failure' of South African local government, as experienced in the SRVM case

Source: Adapted from Clifford-Holmes.[74]

However, *water revenue* is determined by the proportion of billable water for which the municipality actually 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*). When little to no water revenue is ringfenced, 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.

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 overextending 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**

infrastructure overuse on supply. 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 infrastructure overuse on obsolescence**.

Ongoing maintenance can mitigate this effect, but maintenance is also contingent on technical staff capacity. The *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 (including routine and non-routine maintenance). In addition, a reduction in these activities influences 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 6.6 – became the primary endogenous driver of municipal crises explored in the MoF model.

Over the course of the September 2014 disruptions in municipal water service provision (and the associated protests), the MoF model was used as a tool to effectively communicate the causes of local water services system failure to different audiences.[75] The audiences included regulators and managers from national government as well as technical officials employed by the SRVM. The model was co-presented by researchers and a municipal official at a national-level 'Water Dialogue' where the systemic factors underlying water service failures were discussed. Different versions of the CLD shown in Figure 6.6 were also used, along with stock–flow diagrams and outputs from the simulation model, to pose questions and engage with different stakeholders at a local level in the municipality (including civil society organisations and private sector representatives).

The modelling initiatives in the SRVM did not follow a traditional group model-building (GMB) format (as introduced earlier). 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.[76] The SD models (including the MoF model) were then used to support the larger action research process as 'boundary objects'. This modelling approach, which is described further by Clifford-Holmes et al.,[77] was taken forward and used in an expanded form in the third and final case study described in this chapter, as described below.

6.8 Case study 3 – Enhancing resilience in the Limpopo–Olifants catchment

Many of the key challenges facing resource management in South Africa are illustrated in the Olifants River catchment, where attempts to reconcile water demands with available supply occur in a fraught governance context characterised by severe capacity constraints with limited skilled human resources. When the potential effects of climate change are additionally considered, then the requirements for catchment-based management and adaptive, long-term strategies become clear. The Resilience in the Limpopo-Olifants Basin (RESILIM-O) programme was initiated in 2013 in order to support the use of adaptive practices of resource management in the Olifants that are locally-appropriate, tenable and feasible. The RESILIM-O programme is funded by the United States Agency for International Development (USAID) and is implemented by a South African NGO, the Association for Water and Rural Development (AWARD). At the time of writing, the programme is ongoing and scheduled to run to 2018.

RESILIM-O aims to engage resource management challenges in the Olifants catchment holistically. For this reason, the overall programme is underpinned by systems thinking and social learning. The programme began using a customised form of SDM in 2015, after extensively assessing different modelling platforms and approaches (detailed in Pollard et al.[78]). The choice was based primarily on the ability of SDM to support the process of coming to a shared and integrated understanding of problem causes and effects, and to then support coherent planning and the associated actions. The case discussed here outlines a pilot study of the SDM process of RESILIM-O, as run in a sub-catchment of the Olifants River. The case demonstrates the use of SDM primarily as a tool for scenario thinking and in order to mediate and broker between stakeholders (see Figure 6.1).

The Ga-Selati (or 'Selati' for short) is a sub-catchment in the lower-third of the South African portion of the Olifants River basin (see Figure 6.2). Like the Pongola, the Olifants River is another transboundary watercourse where the crossing of international boundaries provides an additional class of complicating factors. Land uses in the Selati catchment include agriculture, game ranching, mining, urban settlements, and conservation. Central resource management challenges pertain to ephemeral river flow; fluctuating water quality; management of wastewater by communities, municipalities, industries and mines; and downstream reliance on the Selati for environmental flows.[79] The connecting theme between these resource management challenges is water security and water use within the Selati catchment in relation to water requirements downstream of the confluence of the Selati and the Olifants rivers (including the water requirements of the world-famous Kruger National Park and the requirements of Mozambique downstream). With the SDM pilot, RESILIM-O undertook exploratory modelling bounded by the following question:

> How, under conditions of climate change, can the requirements of users and ecosystems within the Selati catchment be sustainably met while ensuring environmental requirements for flow and water quality are met downstream?

A summary of how the SDM process has rendered the impacts of the main activities on the Selati River is shown in Figure 6.7. Note that this is presented as a *sector diagram*, which is a higher-level summary of a CLD that shows the main sub-systems and the relationships between them without detailing the causal relationships

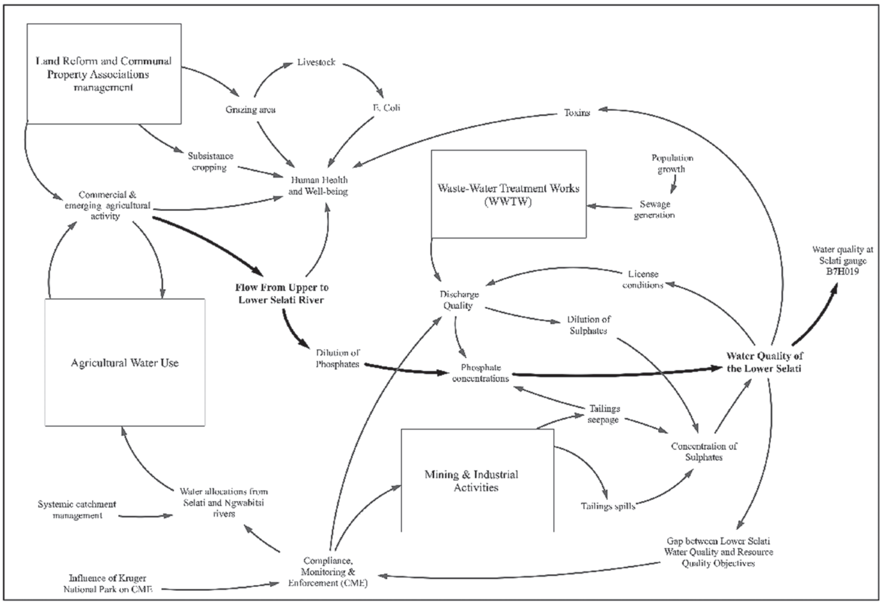

Figure 6.7 Sector diagram of the activities influencing the Selati River. Note that WWTW represents the sanitation sector.

Source: Adapted from Jonker et al.[80]

or the specifics of each sub-system. The sub-systems in Figure 6.7 include agricultural water use (both of small-scale farmers and larger commercial farming operations) and the impacts of waste-water treatment works (WWTW), and mining and industrial activities, on the concentration of phosphates and sulphates, respectively.

The main indicator of system performance in Figure 6.7 is the water quality and quantity at the Selati gauge (referenced as *B7H019*). This is the gauging station at which samples are taken in order to measure the outflowing water quality from the Selati River at its confluence with the Olifants River (shortly before the latter flows through the Kruger National Park). The Olifants River is one of the main arteries of the park, bearing significant recreational and aesthetic value for eco-tourism and subsequently, for the economy of the entire region.

The modelling approach followed by the RESILIM-O team was significantly influenced by two traditions: the first was participatory approaches to development and natural resource management; the second was collaboratively modelling in the SD field (including group model-building and the other approaches discussed and referenced above). As with the SRVM project, the RESILIM-O team developed a portfolio of small models that were co-constructed to varying degrees with the participation of a broad range of stakeholders. Rather than bringing all the groups together over the course of the project, the team ran individual workshops and 'working sessions' and then cumulatively brought stakeholders together (first grouping them within sectors – such as mining, conservation, agriculture, wastewater treatment and management – and then bringing them together on a cross-sectoral basis as a multi-stakeholder group).

The choice to interact with various stakeholder groups on each of these small models, rather than with all stakeholders simultaneously through a traditional group model-building process, was motivated by the socio-political context in the Olifants River basin. This context is characterised by many conflicting users who are divided along multiple lines (racial, ethnic, linguistic and economic). Manifestations of conflict abound, ranging from violent service delivery protests to xenophobic actions, and from political in-fighting and endemic corruption to lawsuits between actors. Furthermore, the levels of numeracy and computer literacy within, and among, stakeholder groups vary substantially. Undertaking a typical group model-building process with such a heterogeneous group of stakeholders – some of whom are technically-oriented engineers and commercial farmers, and others of whom have little experience using computers – was deemed inadvisable.

System dynamics modelling is employed in RESILIM-O using a 'parallel modelling' approach in which a stakeholder consultation and engagement process is undertaken in the foreground while, simultaneously, an underpinning integrative simulation model is developed by specialists in the background. In this approach, SDM is firstly used to support the engagement sessions, each of which is crafted to fit the different characteristics and needs of the participating stakeholders. These sessions are designed by drawing partly on SDM tools and resources – including an encyclopaedia of group model-building 'scripts'[81] – and partly by drawing on practices of developmental planning (including participatory mapping and institutional analysis). Many of the small models developed for these engagement sessions (or co-developed within the engagement sessions) are construed as 'toy models'[82] (i.e. 'not necessarily designed to be reused outside of the context for which they have been designed'[83]).

The second part of the parallel modelling approach involves the development of the simulation model called 'ResiMOD'. This simulation model is influenced by hybrid modelling approaches, drawing conceptually and empirically from other modelling platforms and models used within RESILIM-O, including:

- GIS-based land use modelling;
- Downscaled global circulation models; and
- Hydrological and water quality modelling.

Of these, the Water Quality Systems Assessment Model (WQSAM) is the most significant. This mature systems model has been developed and used throughout the RSA and is linked to a hydrological yield model.[84] By drawing on these existing modelling efforts, ResiMOD can avoid needing to include detailed biophysical modelling and can focus on representing the decision rules and the actual practices of water-impacting stakeholders in the Selati catchment (as they are raised through the iterative stakeholder engagement process and as represented in the portfolio of small models).

This parallel modelling approach is being monitored and evaluated on an ongoing basis as part of the RESILIM-O programme.[85] The monitoring and evaluation process aims to track the learning of participants throughout the process, assessing in what ways the SD-based efforts help develop the capacity of key stakeholders to think, plan, and act systemically. The implications for developmental planning arising from this case study are discussed, along with the implications from the other two case studies, in the concluding section below, in which the case studies are related to one another and to the conceptual framing in Figure 6.1.

6.9 Concluding discussion

A commonality of the three case studies described in this chapter is their location within broader processes. In the Pongola case, it was a larger research project funded by South Africa's Inland Water Ecosystems National Programme for Environmental Sciences in the mid-1980s; in the Sundays River case, SDM was used within the context of a transdisciplinary, action research project funded by SANPAD; and in the Selati case, SDM is being employed within the context of a broader development programme funded by USAID.

As noted by Clifford-Holmes,[86] much of the value of modelling in the SRVM case can be described as providing a 'systematic way of developing a more comprehensive understanding of key aspects of the problem'.[87] All three of the case studies were undertaken within multi, inter, or transdisciplinary environments, in which modelling provided a means of understanding and responding to complex real-world problems, synthesising knowledge, and providing potential decision support (see Badham[88] and Figure 6.1).

In the Pongola case, SDM outputs helped inform a re-evaluation of the operational policies governing flood releases (which was an impressive outcome); from a process perspective, the modelling efforts were integrative, synthesising knowledge drawn from different specialists and fields.[89] As discussed by Ford,[90] one of the substantive benefits of employing SDM as an integrative tool is the breadth of information sources that can be drawn upon in developing models. The fact that 'soft' data can be elicited from, or co-developed with, stakeholders in group processes is particularly noteworthy and relevant in data-scarce contexts such as African water and coastal management (for example, where clean and complete hydrological and social data sets are typically lacking). In the absence of these numerical data sets, techniques that allow for drawing from, and integrating across, multiple information sources are of real and tangible value for developmental planning.

A further commonality across the case studies is the use of participatory approaches to modelling as means of facilitating strategic conversations between stakeholders.[91] This is particularly true for cases 2 and 3, which are influenced by the GMB tradition that emphasises modelling as a learning activity. In the SRVM case, the modelling efforts informed mediation and brokerage activities between conflicting stakeholders, where the model representations were used as 'boundary objects' in discussions with conflicting groups around the time of the September 2014 protests. In the RESILIM-O case, the modelling process interacts with stakeholders in rounds, moving from individuals to sectors, to cross-sectoral interactions. Here, both the portfolio of small models and the underpinning integrative model are aimed at creating shared focal points between stakeholders. This reflects the use of models as boundary objects where 'evolving representations create a shared focus, lend themselves to multiple interpretations, and serve as memory anchors for complex iterative conversations about dependencies'.[92] The use of modelling in this way fits squarely within continuum 3 of the conceptual framing in Figure 6.1.

The RESILIM-O case study also speaks to the importance of designing modelling processes in ways that are cognisant of power dynamics. As noted elsewhere, public participatory processes are inevitably messy:

> Public participation remains a craft, not a science… it [deals with] the messy emotional stuff of intense human interaction, struggles for power, and strongly-held beliefs about what's good for our societies.[93]

This is held to be particularly true in socio-political contexts like South Africa's, characterised by a divisive past; politically-charged decisions around resource management and service delivery; ongoing social traumas and state instabilities; and poverty-driven imperatives for job creation and economic development. These socio-political factors interface with a resource base that has its own complex ecological dynamics. The use of SDM to support and underpin modelling processes in the African water sector will need to be aware of these complexities (as the cases described in this chapter indeed aimed to be).

One of the benefits of system dynamics modelling is the extensive literature and toolkits available to help in these situations.[94] However, few (if any) of these resources were developed in Africa; the majority originate from modelling communities in the developed world (in particular the US, France, the Netherlands and the UK). Although modelling capacity in general, and system dynamics modelling skills in particular, remain in scarce supply on the continent, important efforts are underway to increase this capacity through the further development of international networks and collaborations, as well as additional training becoming available in the higher education sector (as described elsewhere in this book).

Finally, this chapter has sought to show that for modelling to be of use in developmental planning in the water sector, the technical process of model development needs to be paired with sensitive facilitation and careful process design. While system dynamics modelling is not a 'silver bullet', it offers a powerful combination of tools and processes that can be effectively used in diverse settings for strategic and planning processes.

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