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**Climate Change Adaptation in Rural South Africa: Using Stakeholder Narratives
to Build System Dynamics Models in Data-scarce Environments**

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Abstract

The need for innovative approaches incorporating combinations of human and natural pressures for governing and managing water resources more systemically is well established. Participatory modeling has been found to support stakeholder involvement and integrated analysis. However, the uptake of systemic participatory modeling tools within high-conflict, data scarce contexts – especially in the developing world – has been limited. The need for participatory, systemic approaches is essential for addressing deteriorating water resources globally. This study uses narratives to build a system dynamics (SD) model, *ResiMod*, within a participatory process. The novel participatory modelling process was driven by challenges facing the lower Olifants River Catchment in South Africa, including; exceedance of sulphate and phosphate concentration limits, paucity of numerical data and a high-conflict stakeholder mix. This paper demonstrates how narratives can inform, and be informed by iterative model development. *ResiMod* enabled the exploration of perceptions of causality, connections between stakeholder sectors, and potential mitigatory actions that respond to climate-change driven impacts to biodiversity. Furthermore, the process enabled cutting-edge scientific discoveries to be incorporated alongside learning and management insights. The combination of narratives and SD modeling offers a promising approach to support improved communication and learning in high-conflict, data-scarce contexts.

Keywords: participatory modeling, climate change, narratives, system dynamics modeling, water resources management, water governance

1. Introduction

The complex interplay between human needs for water as an essential natural resource and contamination of land and water resources from anthropogenic activities is a global challenge. Recent research from the World Economic Forum (2020) indicates that water crises represent society's greatest challenge, placing them among the top ten global risks. Contamination generated at industrial sites, such as chemical production facilities and large-scale mining complexes, is often perceived as a widespread infrastructural problem compounded by the fact that mitigation of any adverse impacts can be economically challenging (Rügner et al., 2006; McKnight & Finkel, 2013). For example, impacts from acid mine drainage (AMD) produced by mining activities are highly variable as AMD is a product of an array of site-specific properties, which makes predicting the potential for AMD exceedingly challenging and costly (Akcil & Koldas, 2006). Further, systems characterized by a heterogeneous patchwork composed of natural, rural and urban land usage (i.e. peri-urban) are challenging to assess, due to the variety of chemical inputs entering streams, stemming from e.g. agriculture and waste water treatment works (WWTW) (Lemaire et al., 2020; Sonne et al., 2017).

Water resources that are directly threatened by human activities also stand to be further affected by anthropogenic climate change, and devising interventions that will protect freshwater biodiversity and ensure the sustainability of water delivery systems requires frameworks capable of diagnosing the key threats to water security at a range of scales (Sonne et al., 2018; Vörösmarty et al., 2010). As such, there is a need for more systemic approaches that can incorporate the combinations of pressures and their potential intended and unintended consequences, especially where integrated water resources management (IWRM) is concerned (van den Belt & Blake, 2015). The progression of climate change poses significant challenges especially to the IWRM sector of South Africa. The expected impacts include increases in temperature and increased frequencies of severe rain events and periods of drought (Kusangaya et al., 2014) and up to a 60% decline in water yield along the eastern border with Mozambique (Schulze & Davis, 2019). These impacts to natural systems are compounded by both a society struggling with the legacy of post-apartheid inequality and a developing economy (S. Pollard et al., 2014). These interlinking aspects produce a raft of complex management challenges within the water management sector, potentially at a greater scale than is seen in other areas of governance within South Africa (Ziervogel et al., 2014). A substantial and growing body of scientific research has sought to inform adaptive management strategy in the country (Clifford-Holmes, Carnohan, Biggs, Chihambakwe, & Pollard, 2016; Pollard et al., 2014; Pollard & du Toit, 2008; Schulze, 2011). However,

there remains a significant gap between knowledge and implementation – with institutional barriers and poor collaboration playing a key role (Koelble & Siddle, 2014; Mehta et al., 2014; Ziervogel et al., 2014). Notably, this gap between scientific assessment and policy implementation has been identified worldwide as a critical barrier to achieving environmental policy goals affecting water resources (Carvalho et al., 2019).

Recognition of the roles institutions and individuals (e.g. stakeholders) play in the implementation of water management strategies has also been in focus globally, featuring in multiple initiatives including the European Water Framework Directive, U.S. Clean Water Act, and the UN Sustainable Development Goals. With respect to water resources, participatory modeling processes “have been found to be a useful methodology to support stakeholder involvement and ensure a more integrated analysis” (Halbe et al., 2018). Participatory modeling has been applied to water resource challenges for more than two decades (Ford, 1996) with increasing application globally (Antunes et al., 2009; Langsdale et al., 2013; Pahl-Wostl, 2015; Stave, 2003; van den Belt & Blake, 2015).

System dynamics (SD) is a modeling practice with a long history of application to IWRM, and its application is increasing (Khan et al., 2009; Winz et al., 2009). SD is a technique that simulates system behaviour based on the servo-mechanical principles of accumulation, delay and feedback (Sterman, 2000). The transparency (Beall et al., 2011) and flexibility (Winz et al., 2009) of SD has led to established and effective participatory methodologies (Rouwette et al., 2002; Rodney James Scott et al., 2016; Vennix, 1999). However, barriers remain that limit further expansion of participatory SD approaches within IWRM, including time demands of stakeholder engagements, context-specificity and short time-frame of participatory modeling interventions (Halbe et al., 2018). Responding to these challenges requires further alterations to methodologies, improving the adaptability of participatory SD to the physical, environmental, socio-economic and institutional circumstances (*ibid.*).

The work reported here draws upon a method which aims to pragmatically adapt participatory SD tools to the “messy operational reality” faced by stakeholders (Clifford-Holmes, Slinger, de Wet, & Palmer, 2018). This approach is used to support novel integration of narratives (i.e. storytelling) to support the development and application of a SD model, *ResiMod*, within a participatory process. The model was developed to support the component action research project known as Collaborative Dynamic Modeling (CoDyM). The primary aims of *ResiMod* were to: (1) integrate perspectives of multiple, diverse stakeholders; (2) improve stakeholder understanding and consideration of possible

climate change impacts; and (3) uncover and communicate learning and management insights through the model-building process and through the resulting simulations (Clifford-Holmes, Carnohan, et al. 2016; Clifford-Holmes, Pollard, et al. 2016).

2. Olifants River Catchment study site

The Selati River traverses an important sub-catchment located within the transboundary Olifants River Catchment (ORC) in the Limpopo Province of South Africa. The Association for Water and Rural Development (AWARD) initiated the participatory SD process as part of the USAID-funded Resilience in the Limpopo-Olifants basin (RESILIM-O) programme, which aims to improve resource management in the ORC. The catchment is beset with diverse management challenges: the need to improve water security must be balanced within a contested governance context, which currently faces severe capacity constraints. These capacity constraints affect physical and operational capacity for water sanitation services (Department of Water Affairs, 2011; Kings, 2017). Of the estimated 120 WWTWs in the ORC, many do not comply with national benchmarks. Of those assessed for waste-water quality compliance in 2011 in the case study area, compliance was only achieved 20% of the time (Hansen & Pollard, 2015). Additional constraints include a lack of ‘clean-up’ funding allocated to ageing mining and industrial sites and weak enforcement and implementation of environmental regulations (Dippenaar et al., 2005). Stakeholders span agriculture, mining and industry, conservation and municipal water supply and sanitation.

Existing models have been used in the ORC to investigate water quality parameters indicative of the activities of these stakeholder groups (e.g. sulphate, phosphate, nitrate) (Slaughter et al., 2017). However, the diversity of roles and governance levels within and among these stakeholder groups leads to difficulty in navigating conflict-riddled communication pathways, hampering efforts to reconcile crises occurring across the catchment (Clifford-Holmes et al., 2016; S. Pollard & Laporte, 2015). The overall problems faced become even more vexing when water security is considered in the context of the potential effects of climate change, where the ORC is projected to experience higher temperatures and intense rain events (Climate System Analysis Group (CSAG), 2016; Pollard et al., 2020). When this amalgamation of pressures is considered, there is a clear need for novel approaches to support adaptive catchment-based management across time-scales (Clifford-Holmes, Pollard, et al., 2016; Pollard & Laporte, 2015).

The Selati River joins the Olifants River before passing through Kruger National Park (KNP), and crossing into Mozambique (Figure 1). KNP is internationally renowned as a beacon of biodiversity but its downstream location makes it highly vulnerable to impacts from the upstream activities of multiple actors along the Selati. To date, various contaminant inputs along the Selati and elsewhere in the catchment have had negative impacts on KNP biodiversity (Centre for Environmental Rights (CER), 2016). Earlier work scoped supported the identification of stakeholders that should engaged in building ResiMod (Clifford-Holmes et al., 2016). Priority stakeholders were identified from the Ba-Phalaborwa wastewater treatment works (WWTW), Phalaborwa Mining and Industrial Complex (PMIC), and Kruger National Park (conservation).

Figure 1. Hydrological boundaries of the Selati Catchment of the Limpopo basin, South Africa.

3. Methodology

A blend of approaches and tools was used to build ResiMod, emerging out of necessity due to the characteristics of the case study site including a restrictive timeline (three months) for completion of the field work within the RESILIM-O project. The paucity of written and numerical data to draw from, resulted in an increased dependency on stakeholders' knowledge of the catchment in order to define the structure of the system and support interpretation of the resulting model behaviour. SD was chosen as the main modelling method due to (i) its suitability for exploring long time frames (~50 yr); (ii) ability to deliver insights about the non-linear system-wide interactions that may lead to unintended consequences, and (iii) its patent focus on espousing the relationship between system structure and behaviour (Forrester & Senge, 1980). These characteristics developed into several participatory disciplines – granting access to a diverse library of tools for stakeholder engagement. SD was therefore preferred, given the long time-horizon under consideration (with respect to climate change), as well as the diverse levels of expertise of the stakeholders. Furthermore, complex spatial interactions, where other methods excel (e.g. agent based modelling), were not a focus of this study (Voinov et al., 2018).

3.1 Narratives and System Dynamics

The concept of applying narratives (i.e. stories) to communicate scientific insights has been increasingly explored (Avraamidou & Osborne, 2009; Dahlstrom, 2014; Krzywinski & Cairo, 2013). The definition of narrative communication is often given in relation to Bruner's 1986 framework for how

humans organize information (Avraamidou & Osborne, 2009). Bruner's framework differentiated between paradigmatic, or reason-based, logical, scientific constructions, and narrative, which "refer[s] to a way of sculpting and structuring information [...] into readily understood forms that guide learners' comprehension" (Avraamidou & Osborne, 2009). Where paradigmatic communication strives for generalizability and being context-independent, narrative is specific and context-dependent (Dahlstrom, 2014). Narratives have previously been viewed in a poor light, as they are inherently persuasive and can therefore be manipulative (Dahlstrom, 2014; Katz, 2013). However, the strengths of narratives have also been examined, for example, Tsoukas and Hatch (2001) argue that narrative modes of communication take into account context, human agency within that context, and temporal characteristics, which are absent from paradigmatic communication. This is a crucial factor when analysing decision scenarios in complex problem spaces. Furthermore, the inclusion of these characteristics can be used to support linkages between system elements (Tsoukas & Hatch, 2001) and, by extension, between actors and the system under observation (Flyvbjerg, 2004).

The benefit of blending narratives and simulation has been explored using a variety of modeling approaches. Alcamo (2008) developed a framework and approach called "storylines and simulation" (SAS), aimed at coupling quantitative models with qualitative narratives. Drawbacks to SAS include the time-intensiveness of the development process for both aspects (narrative; simulation), inflexibility of modeling approaches, and challenges with reproducibility due to lack of transparency. Following the SAS framework, recent participatory modeling studies have used approaches to combine narratives and simulation successfully. For example, Houet et al. (2016) apply narratives using several models at multiple scales. However, they note limitations related with the application of their approach to developing country contexts and argue for more participation with stakeholders.

Participatory SD has historically sought to align participants' mental models, or "relatively enduring and accessible, but limited, internal conceptual representation[s]" (Scott et al., 2014), using SD simulation models and structured processes. Mental models and narratives are quite similar in their definition. For example, Oatley (1999) likens a narrative to a "simulation that runs on minds of readers just as computer simulations run on computers." SD modeling as a method and discipline exposes the relationship between individual agency (decisions) with the operations of the system at-hand (Olaya, 2015).

The use of SD modeling in a participatory fashion can stimulate cognitive conflict, a beneficial aspect for improving the quality of group decisions (Vennix, 1996) and allowing all individuals a chance to take part in the discussion, which promotes consensus-building (Korsgaard et al., 1995). Our approach to building ResiMod utilizes both of these aspects, aiming to build consensus by incorporating diverse stakeholder narratives into the model and use the resulting simulations to challenge their mental models (i.e. cognitive conflict). In this way, we sought to challenge individual views in order to support consensus-building and communication among the larger group.

In summary, the development of ResiMod is distinguished by the explicit integration of narratives as key inputs into the participatory SD modelling process (see Figure 2). This is a novel approach which has been relatively unexplored (Guhathakurta, 2002; Mallampalli et al., 2016). Furthermore, the similarity of narratives and mental models makes SD a preferable tool to explore this integration - due to the established effectiveness of participatory SD modelling in creating enduring changes to mental models (Scott et al., 2016).

3.2 The “Muddled Middle” Approach

The approach to model building and stakeholder engagement was rooted in the “modeling in the muddled middle” or M³ approach, which integrates ethnographic, institutional and systems analyses, recognizing that modeling can serve many purposes from supporting process to delivering analytical results (Clifford-Holmes et al. 2018). The M³ approach allows for construction of multiple smaller sub-models, following best-practice SD modeling (Ford, 2010; Sterman, 2000). With ResiMod, initial causal loop and stock-and-flow (SF) diagramming set the stage for parameter estimation and simulation. The M³ approach was adopted to fit the socio-political context, which is “characterised by multiple conflicting users who are divided along multiple lines (racial, ethnic, economic and nationality)” (Clifford-Holmes et al., 2018; Zolfagharian et al., 2018). During the problem scoping phase of the modeling process, focus shifted towards the lower-Olifants, where some of the greatest impacts to water quality had been experienced, in the form of sulphate and phosphate concentrations exceeding legislated values (Clifford-Holmes, Pollard, et al. 2016). For the construction of sub-models, stakeholders were divided into common interest groups and meetings were conducted both individually and in groups (Table 1). Such a strategy has been successfully applied previously in case study settings using SD, where diverse “fragmented” stakeholders are represented in the process (Eker et al., 2018).

Table 1. Meetings were arranged flexibly, following the M³ approach, to maximise data collection in the limited time-period.

216

217 **3.3 Integrating Narratives and Participatory SD**

218 Within the individual working sessions (see Table 1), simple concept models were often
219 introduced using a stock and flow diagram (SFD) (see Table 2) (Richardson, 2013). However, this was not
220 always possible or useful due to time constraints, or challenges in conveying the message through
221 diagrams. For these situations, an unstructured interview strategy was chosen, since this method is
222 regarded as advantageous for eliciting participants' own reality as a means to develop theory (Fontana
223 & Frey, 2005). In these sessions, a combination of causal loop diagrams (CLD) and hybrid SFDs along with
224 field notes were used to capture the narratives. Sessions typically lasted from 1-3 hours, and towards
225 the end of the interview, the CLD/SF diagram would be reflected back to the stakeholder in narrative
226 form in order to verify that it captured the discussion appropriately.

227 *Table 2. Diagrammatic conventions used in this paper for the stock and flow diagrams (SFDs). Table adapted from (Clifford-*
228 *Holmes et al. 2017).*

229 In follow-up interviews, the disconfirmatory interview strategy was applied to test/verify the
230 developing theory. This strategy includes anchoring participants in specific content based upon their
231 expertise, adapting the interview to the participant, and organizing the interview around the model
232 structure and behaviour. As the narratives and model developed, they could be presented and
233 acknowledged as works-in-progress that may have errors (Andersen et al., 2012). The use of the
234 disconfirmatory interview responds to ethical concerns relating to the inherent persuasiveness of
235 narratives (Dahlstrom, 2014). This approach was performed iteratively, and accumulating information
236 was shared in the sessions that followed. This enabled the exploration of connections between sectors
237 and allowed the perspectives of stakeholders from different sectors to be shared. Thus, narratives both
238 informed, and were informed by the model development.

239 *Figure 2. ResiMod relied on narratives for structuring, with both the narrative and model undergoing iterative development.*

240

241 **3.4 Modeling integration and Climate Change**

242 Many additional data sources were used to supplement interviews for ResiMod, including
243 earlier SD modeling work (Clifford-Holmes, Pollard, et al. 2016) (see section 5), output from the Water
244 Quality Systems Assessment Model (WQSAM) and downscaled climate models. Specifically, water

quantity and quality data were taken from WQSAM, which simulates water quality by receiving flow volumes from a yield model - the Water Resources Modeling Platform (WReMP). The WReMP delivers flow data on a monthly basis, which is disaggregated in WQSAM into a daily time-step to capture transient events required when modeling diffuse and variable loads. (see Slaughter et al. (2017; 2013)). The WReMP model provides WQSAM with monthly flow data as incremental stream flows and return flows. This monthly flow undergoes two transformations; first it is disaggregated to a daily timestep, using observed and simulated (CC) rainfall allowing us to capture transient events (e.g. sulphate mobilisation from a runoff event on a mine). The daily discharge is then separated into surface, interflow and groundwater flow components; this allows us to route pollutants (water quality) along these pathways. Non-point source pollutants are routed through surface, interflow and groundwater while point sources are routed through return flows. By providing the ResiMod with return flow volumes and the receiving river quality and quantity, the end fate load and concentration can be determined and altered according to an intervention strategy, which was calculated by integration with ResiMod (further detailed in the results).

The climate modeling was performed by the Climate System Analysis Group who statistically downscaled climate projections from three General Circulation Models (GCMs), representing medium and high greenhouse gas concentration (not emission) trajectories (Climate System Analysis Group (CSAG), 2016)). In ResiMod, only the downscaled projection for RCP8.5 and the MIROC-ESM GCM was used. The same climate projections were utilised in the WReMP yield model and WQSAM. Importantly, these models and other assumptions regarding the impact of climate change (CC) within ResiMod were used to develop a “CC switch”. This activates a suite of parameter changes, as shown in Table 3.

Table 3. The CC switch engages multiple parameters informed by multiple information/data sources.

4 Results and Discussion

Narrative results are presented, followed by their implementation into the SD structure. Discussion of key assumptions and data sources are given for each sector alongside the corresponding structure. This section thus provides a detailed description of the model logic, establishing the conceptual foundation that was constructed iteratively using the narrative approach. This includes key stocks, flows and feedback loops alongside important parameter assumptions provided by participants or the modelling team (Monks et al., 2019). Following the STRESS-SD guidelines for model reporting

(*ibid.*), additional parameters, equations and detailed descriptions of data sources are provided in *Supplementary Document 1*.

4.1 Mining and litigation

4.1.1 Narrative

Mining tailings waste is a well-known threat to freshwater biodiversity, with seepage and spills delivering sulphates to the Olifants River. Although elevated levels of sulphates can directly impact biodiversity, their persistent presence in water resource systems can indicate that other types of pollutants (e.g. heavy metals) are entering and accumulating in the aquatic ecosystem. Other toxic compounds can enter the stream when spills occur, brought on by flooding which will likely increase under climate change conditions. Spills can have broad negative consequences for the PMIC's bottom line. This is due to media reporting on impacts to biodiversity in the KNP, which can generate public awareness. Past events have shown that mining companies respond more strongly to public awareness pressure than to regulatory pressure. Similarly, impacts to biodiversity generate more public awareness than regulatory exceedances. There are delays in response time before the media disseminates the information to the broader public. While some measures have been taken to prevent these outcomes (e.g. reusing process water) there are still many opportunities for mining companies to mitigate these outcomes. There is an important distinction between reactive mitigation (i.e. *after* pollution event and regulatory action) and proactive mitigation (i.e. *before* pollution event and regulatory action), with the former carrying additional costs through fines and reputational damage. On the other hand, mining companies can proactively develop policies to mitigate the negative environmental consequences of tailings-waste and improve their institutional memory, embedding lessons learned from previous regulatory punishments.

4.1.2 SD structure and parameterization of mining sector

Figure 3 presents the structure and main stocks of the mining sector. The representation of "tailings mitigated" and "unmitigated tailings of PMIC" simplify the fate of tailings-waste. Any unmitigated tailings are representative of the volume of tailings assumed to be prone to seepage and spills, and when tailings are 'mitigated' they can no longer enter the environment. Mitigation is therefore a representation of all the possible activities that may be undertaken by the PMIC to prevent any further release into the environment. A significant assumption is that the model considers these

activities would be 100% successful. This point was initially contested by mining company representatives in a working session, however, further discussion led to agreement that this structure and aggregation level could ultimately represent the effects of their mitigation efforts.

Figure 3. The stock-flow structure of the mining sector separates the volume of tailings (in megalitres) into unmitigated and mitigated fractions. A third stock is used to track the total amount of sulphate (measured in tonnes) released from the dam over the 50-year period.

The “process water reuse” flow was included in order to show PMIC representatives that the modeling team was aware of their efforts to mitigate environmental impacts. The fraction “proportion of tailings water reused” determines both flow rates, as the remaining fraction sets the amount of “water diverted into tailings dam” each month.

A constant value for the “fractional seepage rate” was adopted from earlier modeling work (Jonker et al., 2015). Total sulphate discharge is the product of “seepage” volume and the “sulphate concentration of seepage”. There is an assumption made here that all seepage enters the stream; ResiMod does not distinguish between specific transport pathways. There was a broadly communicated perception of many stakeholders that mining tailings waste has a great impact to the freshwater ecosystem. International headlines reflected this as well, following the 2013/2014 spill events (Centre for Environmental Rights (CER), 2016). In ResiMod, impact was based upon the use of a preliminary species sensitivity distribution (SSD) developed for combined sulphate salts (e.g. Dowse, Tang, Palmer, & Kefford, 2013). Sulphate is recognised as a key component that may additionally influence which processes/fluxes occur in conjunction with contaminant release dynamics (Rinklebe et al., 2016). Notably, these curves have subsequently been revised, as sulphate salts were found to be more toxic than the preliminary data had shown (Vellemu et al., 2017).

An additional stock tracking the accumulation of tonnes of sulphates was added. This was motivated by input from conservation sector stakeholders, who felt that the long-term bioaccumulation of sulphate salts pose an additional threat. The stock variable “Total tonnes of sulphate released over 50 years” was used as a means of promoting conversations about the possible long-term systemic impacts.

4.2 WWTW Sector

4.2.1 Narrative

Population growth leads to increasing demands for WWTW facilities in the local Ba-Phalaborwa municipality. However, the total operating capacity of WWTWs is constrained by the ability to maintain the actual physical WWTW capacity. It takes time to recruit and train staff to handle the required daily operation and maintenance (O&M). Therefore, even though the overall physical capacity of the WWTW in Ba-Phalaborwa may support the population, it may not be operational due to O&M constraints. This trend has been seen due to underinvestment in maintenance and training, in favour of investment in the physical capacity. The result is the release of phosphates into the Selati, compounded by more intense rainfall leading to flooding which overwhelms WWTW. This challenge is compounded because plants which are improperly maintained have shorter operational lifetimes, resulting in a loss of capacity and a failure to maximize on public infrastructure investment. Building new WWTW also takes time and keeping up with forecasted demand requires long-term planning. When WWTW capacity is unable to keep up with demand, excessive phosphate concentrations will then be released to the Olifants River system, adversely affecting biodiversity. This can be mitigated by improving/shortening training, improving operations, and improving maintenance to ensure available physical WWTW capacity is fully utilised.

4.2.2 Structure and parameterization of WWTW sector

Figure 4 presents the representation of this sector within the SD model, as “Total population in Ba-Phalaborwa” drives the demand for WWTW. Data for the ‘fractional population growth rate’ were derived from the Ba-Phalaborwa Municipality Census Data, (2011). The population is multiplied by “sewage per person” measured in litres (l) per day, converted to ML per month. This is the “demand for WWTW” or the amount of sewage produced per month from the “percentage of population connected” and refers to Ba-Phalabowa residents (Holness, 2014; Jonker et al., 2015).

Figure 4. The stock-flow structure showing how population drives the development of WWTW.

“Forecasted demand” is based on the current “total capacity” of WWTW. The ‘time horizon’ is how far into the future the demand forecast is made and a longer horizon leads to a higher forecasted

demand. This leaves remaining ‘indicated physical capacity’ that should be developed in order to meet the forecasted demand. The planning horizon guidelines indicated that a horizon of 10 years is standard (Nozaic & Freese, 2009).

Figure 5 presents the operations and maintenance (O&M) capacity of WWTW, which was added to the model based on input from the retired WWTW supervisor and supported by literature (Gopo, 2013).

Figure 5. Stock-flow structure of the WWTW O&M capacity.

The O&M capacity is used to capture the overall ability of the managers, operators and general maintenance staff to operate and maintain WWTWs. Human resources were one of the main issues under scrutiny by regulators while ResiMod was under development. Stakeholders lamented that improvements are only likely over a very long time-horizon (captured in the 'time to train and update O&M capacity' variable). Furthermore, the structure captures the WWTW consultant’s indication that regulatory incentives have led to an overemphasis on increasing technical capabilities of plants without improving staff recruitment and training . The consultant validated the vicious cycle that this creates, where more failures take place along with increasing infrastructure capacity and that these failures then motivate funding applications for more physical capacity (Carrim et al., 2010; Manus & Van Der Merwe-Botha, 2010).

The notion that such capacity has been largely underemphasized is a key part of the model narrative as told by many of the stakeholders in the WWTW sector. Therefore, the “hiring new O&M capacity” is constrained by both hiring and training delays and the lack of emphasis on human resource development as “fraction of O&M supported”. The initial value estimate for this stock was developed with the WWTW policy consultant and calculated to be 60% of total WWTW capacity (see Figure 6).

The physical capacity (Figure 6) is categorized as either online, and therefore treating wastewater generated by the population, or offline, i.e. inoperable for any number of reasons. More specifically, “WWTW physical capacity online”, refers to the plant’s total capacity to physically process incoming sewage to meet legislative benchmarks for phosphate concentration (*Requirements for the Purification of Waste Water or Effluent*, 1984). For both the online and offline capacities, data for WWTW plants servicing the Ba-Phalaborwa Local Municipality (BPLM) were used to set initial values (Ba-Phalaborwa Municipality, 2015).

Figure 6. Stock-flow structure of the WWTW physical capacity, including assumptions regarding the rate of failure and decommissioning.

Other key variables include the “new physical capacity”, which refers to the construction of additional WWTW capacity. Capacity is added based on the forecasted demand and policy of investment as “fraction of physical development need supported”. ‘O&M capacity available for maintenance’ is the difference between the physical capacity online and the O&M capacity. It assumes that operating online capacity takes an equivalent amount of O&M. The remaining O&M capacity is free to perform any necessary maintenance tasks driving the “repair rate of WWTW”. This is adjusted by the “final infrastructure efficiency factor”, which allows the user to simulate scenarios where technologically advanced WWTW plants could be installed requiring less O&M capacity to operate effectively.

The WWTW policy consultant further described the effect of O&M maintenance on the lifetime of the plant. In this case, she confirmed that the “ratio of O&M to capacity” was a useful measure of the routine maintenance capability. The consultant worked directly within the model to help define the graphical function for the “effect of O&M ratio on average life of plant” and verified the behaviour of the resulting simulations.

4.3 Biodiversity Sector

The biodiversity sector uses metaphor to promote familiarity for the variety of stakeholders involved in this catchment. Freshwater riverine ecosystem biodiversity, or FRED, is a central indicator in ResiMod (see Figure 9) and was developed from an earlier indicator of aquatic biodiversity in the Kruger National Park (KNP). In engagements with KNP representatives, the term FRED was suggested as a “friendly” or neutral acronym aimed at more broadly representing aquatic biodiversity. Since the KNP had played a significant role in the pursuit of penalty fines passed down to some companies following one particularly damaging spill event (Centre for Environmental Rights (CER), 2016), they wished to avoid politically and personally charged future discussions that might emerge if their interests were directly named. Therefore, FRED was anthropomorphised (Figure 7) and presented within a short video to support the biodiversity narrative.

Figure 7. Freshwater riverine ecosystem biodiversity (FRED) was communicated as an anthropomorphised character.

4.3.1 Narrative

FRED supports the delivery of a wide variety of ecosystem services. This includes household use and irrigation, as well as supporting freshwater biodiversity and ecotourism. FRED is impacted by excessive loads of sulphate and phosphate, reducing his ability to provide these services. FRED can recover as a result of remediation efforts as well as through natural processes, but these are both time-intensive (and costly) options. Therefore, ensuring the “health” of FRED is an immediate priority to ensure long-term sustainability and use of water.

Figure 8. Stock-flow structure of the Freshwater Riverine Ecosystem Diversity formulation, including use of species sensitivity distributions.

4.3.2 Structure and parameterization of the biodiversity sector.

The biodiversity sector integrates the in-stream loads from WQSAM and the load calculated by ResiMod. The “combined concentration...” variables calculate the total in-stream load using data from WQSAM for pollutant loads (sulphate; phosphate) already in the river (in-stream load), with additions from ResiMod sub-modules. The final concentration is calculated using WQSAM flow data. Thereafter FRED is updated via the SSDs, that deliver the percentage of species affected at a given concentration. FRED is therefore quantitatively represented as a percentage ranging from 0% (complete biodiversity loss) to 100% (best ecological condition, “desired level of FRED”) and indicates the proportion of FRED that is intact (Figure 8). Historical data taken from WQSAM from 1950-2000 serves as the business as usual (BAU), and WQSAM climate change (“CC”) variables contain time series data generated from 2010 to 2060, which includes the downscaled GCM.

Three SSDs were implemented in ResiMod corresponding to the upper, central and lower tendency values corresponding to the 95% confidence interval (Vellemu et al., 2017). In order to simulate worst- and best-case scenarios regarding impacts to biodiversity, the “conservation emphasis” graphical lookups use the lower limit of the 95% confidence interval to assume the sharpest effect on biodiversity. The “conservative” and “intermediate” use the upper bound and central tendency, respectively. The “effect switches” allow the user to select the level of impact used in the simulation. During a workshop with the conservation sector, stakeholders chose the “intermediate” sulphate and “conservative” phosphate SSDs for the BAU simulation.

The “conservation pressure on regulators due to FRED impacts” is a variable that is inversely related to impacts on FRED. It is an assumption made to represent the operational reality of the conservation sector’s main leverage to enact change – in their role as a key-player applying pressure on regulators to initiate litigation of mining and industrial companies.

4.4. Narratives and simulation using ResiMod

The key narratives were developed according to each sector with substantial overlap across the sectors. This resulted from the narratives being shared within and between sectors throughout the development of ResiMod. These narratives were then synthesized into an overall systemic narrative that was used to frame the facilitated group work in a final workshop, conducted among representative stakeholders from all sectors.

Figure 9. The feedback loops identified within ResiMod. Yellow connections form feedback loops within the mining and industry submodule, green connections are feedback loops within the WWTW submodule, and the blue feedback loop is within the biodiversity submodule. Connections with double perpendicular lines indicate that delays are present in those feedback loops.

Figure 9 summarises the system structure of the final model indicating relationships and feedback loops corresponding to the structure of the final model. While WQSAM provided initial in-stream load conditions, endogenous behaviour driven by these feedbacks produces scenario results in response to parameter input. Scenario input was driven by stakeholders, as groups were tasked with making consensus decisions concerning which policy levers (middle of Figure 10 and in (red) italics in Figure 9) ought to be modified in order to improve outcomes over the base case scenario. Before each model simulation, stakeholders were asked to perform their own mental calculations (Ford, 1996) and discuss potential outcomes. The CLD (Figure 9) was utilised as a tool to trace consequences of their group decisions through overall feedbacks within the model. In this way, simulations were used to challenge stakeholders’ mental models and initiate discussions about the relationship between system structure and simulated behaviour.

Simulation results for ResiMod are shown in Figure 10. Within the tradition of SD (and with reference to the purpose of ResiMod described previously), verification was not pursued as point predictions, but as qualitative assessment as to whether the model structure and resulting behaviour patterns are qualitatively correct (Barlas, 1996). This falls within the scope of pattern-prediction and

event-prediction tests (Forrester & Senge, 1980). Due to the paucity of data for key indicators, the model behaviour was verified primarily by stakeholder input.

The overall finding was that policies combining multiple mitigative actions are needed to combat freshwater biodiversity losses. Four scenarios are shown in an additive fashion (Figure 10): FRED gradually declines under the BAU scenario, but the decline is sharper with climate change impacts. Improvements to the management of the mining and industrial sector contribute significantly (scenario 3) but systemic improvements (scenario 4) are most effective at improving FRED.

Figure 10. Simulation results for ResiMod displays examples of policy scenarios. Each run represents the corresponding scenario shown in the included table. Policy levers are visible in the middle panel, purple levers correspond to the mining and litigation sector, brown correspond to WWTW sector and green corresponds to the biodiversity sector. Lever descriptions are presented in detail on the online interface (<https://exchange.iseesystems.com/directory/jai>). Scenarios are additive: climate change incorporates changes detailed in Table 3; scenario 3 includes climate change plus 3 additional changes (a, b, c); scenario 4 adds additional parameter changes to WWTW (a, b, c). The key indicator, FRED (panel A), is improved by reductions in mining tailings waste (lower left, panel B) and improvements to the function of WWTW (lower right, panel C). A prominent example of the interplay between policy levers and simulation results is noted by the vertical black bar in panel A at month 60 (year 5), where a marked increase in WWTW capacity is triggered by an increase in plant efficiency which becomes available in the selected “efficiency start year”.

Participants experimented with policies by toggling parameters as a group, learning through simulation and discussion that combined actions were the most effective for improving FRED. For example, simply increasing the efficiency of WWTW plants (i.e. a technological solution) was ineffective without boosting investment in O&M and reducing staff training times. This is because such a combination of policies prevents the balancing loop controlling the online physical capacity of plants from drifting to low performance. However, some levers had little impact, even when applied in combination. For example, the “advocacy and public awareness” lever generated only minor improvements in FRED. This is due both to the numerous long delays involved in these feedback loops, and the low responsiveness of both WWTW and mining and industrial sectors to public awareness.

4.5 Parallel Evaluation using the Monitoring Evaluation Reporting and Learning Framework

Evaluation of the CoDyM program and ResiMod was conducted within the Monitoring, Evaluation, Reporting and Learning (MERL) framework ongoing within RESILM-O (AWARD, 2017). MERL was developed to improve evaluation and effectiveness of long-term programs carried out in complex problem spaces. It is a parallel monitoring approach that uses both quantitative and qualitative methods to continually assess the benefits or drawbacks of activities carried out within project activities and adapt activities based on collective lessons learned (USAID, 2018). For CoDyM, a qualitative content analysis approach was applied to all documents related to the project, including notes and meeting minutes. This was a theory-driven coding exercise that reported the successes and limitations of the approaches taken within CoDyM, including the unstructured interviews that delivered the narratives along with the resulting utilisation of ResiMod within workshops.

The MERL evaluation indicated that the use of ResiMod in the final workshop was successful in supporting the development of participants' understanding regarding climate change impacts on water resources. Furthermore, participants commented on the beneficial nature of understanding the "system as a whole" and having their mental models challenged. They were surprised that some variables had less influence on simulated results than expected, leading them to reconsider the problem and consider the validity of results more holistically. Communication techniques were also addressed by MERL, and the presentation of different viewpoints via the synthesized narrative was regarded as an enjoyable learning experience that helped some participants understand how other sectors think. It also left participants feeling that their network had expanded (Kotschy, 2016). Selected comments from the workshop further support these results:

- *"I learned more about climate change and know its impacts on our waste water plants";*
- *"It was very interesting to note that climate change links to [other] sectors";*
- *"Making climate change practical and [finding] solutions on the ground [was valuable]";*
- *"The value of dynamic modelling to drive decisions and test results";*
- *"[I] think that running this model and factoring in the climate change factor will improve horizon planning and developing more resilient management plans";*

- *“... fabulous to dwell on the fact that climate change can be an opportunity – crises can be [a] kind [of] opportunity to coalesce around”.*

Overall, ResiMod was considered instrumental within CoDyM. As Kotschy (2016, p. 25) noted, “the value of [CoDyM] really lies in the possibility for developing a tool which can help stakeholders from different sectors to confront the impacts of their own practices and to explore options together”. Moreover, the fact that representative stakeholders from each sector were present and engaged in the final workshop indicates that ours was a promising approach to support improved communication and learning among high-conflict groups, within data-scarce environments.

5. Discussion, conclusions and future work

This paper has demonstrated a novel approach using narratives to support SD model development and communication bi-directionally. This responded to the needs of the context and catchment and required trade-offs to engage a diverse stakeholder base with high-conflict potential, in a short timeframe and with limited data. One key strength of this work is the unique ability of SD to support integration of narratives with the flexible M³ participatory approach. This allowed a small modeling team operating in a high-conflict catchment to support stakeholder communication and facilitate insights about the impacts of climate change and what stakeholders could do about these impacts.

The case study catchment in South Africa is characterised by complex governance challenges - impacted by multiple stressors, with multiple actors and high conflict potential. This same characterisation can describe many natural resource governance contexts around the globe. Therefore, the approach used to develop ResiMod, though not without limitations, can provide useful guidance for modelers and participatory SD practitioners in other settings. Narratives and storytelling are some of humanity’s oldest communication methods. This study has shown how they can be successfully translated into a quantitative simulation model, with results made understandable to stakeholders with a history of conflict as well as differing technical acumen.

In some cases, the use of a simulation model limited the flexibility of the modeling team to respond to individual stakeholder needs (Kotschy, 2016). The erratic timing of stakeholder involvement (i.e. joining late or dropping out of the process), also added challenges. For example, the narrative surrounding the mining sector and possible actions was constructed with a paucity of input from the stakeholders until the later stages of model development. This created an unequal sharing of

information and may have led to an overemphasis on the WWTW sector at earlier (and later) stages of model development and use. Furthermore, ResiMod did not become embedded in stakeholders' long-term decision-making, an ongoing challenge within participatory modeling and associated research (Halbe et al., 2018; Rouwette et al., 2002).

Nevertheless, this study has highlighted that understanding how to adapt participatory modeling processes and tools to stakeholders with different needs and technological backgrounds is crucial. Though this type of model customization can often be time and resource intensive, new technologies and strategies for stakeholder engagement that can develop aesthetically engaging interfaces may help close this gap (Fishwick, 2012). Narratives certainly offer another promising avenue to meet this challenge. Moreover, this study also explored how participatory approaches can help bring cutting-edge scientific information into the decision-making realm faster. For example, the incorporation of SSD curves for sulphate toxicity, which were available only as preliminary data during the development of ResiMod. Developing better theory on when and how to adapt stakeholder engagement processes will require the application of more targeted measurement and evaluation strategies (Zolfagharian et al., 2018). This can improve understanding of how participation, simulation and cutting-edge scientific knowledge can be better linked, and thereby shift scientists' role from data-providers to facilitators of science-driven decision-making (McCown, 2001). One of the established and evolving sources for this are the evaluation methods applied to SD participatory modeling. With deference to narratives, a better evaluation of the effectiveness of the disconfirmatory interview at overcoming their persuasive nature is needed. Such studies could be undertaken within future applied cases or using controlled experimental settings.

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587 **Declaration of Interest**

588 The authors declare no conflicts of interest.

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