The Role of Learning in Water Supply Systems

Analysing the Spread of Policies in Rural Uganda using Memetics

Master Thesis

Felix Knipschild

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Author

Name Felix Sylvester Knipschild

Student number 4034465

Email felixknipschild@gmail.com; f.s.knipschild@student.tudelft.nl

Faculty Technology, Policy & Management, Delft University of Technology

Graduation Committee

Chairman Prof. Dr. ir. P.M. (Paulien) Herder dep. Engineering Systems and Services, Faculty of Technology, Policy & Management, Delft University of Technology

First Supervisor Dr. ir. I. (Igor) Nikolic dep. Engineering Systems and Services, Faculty of Technology, Policy & Management, Delft University of Technology

Second Supervisor Dr. J.H. (Jill) Slinger dep. Multi-Actor Systems, Faculty of Technology, Policy & Management, Delft University of Technology

Third Supervisor D.C. (Deirdre) Casella, MA dep. Engineering Systems and Services, Faculty of Technology, Policy & Management, Delft University of Technology

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Preface

This research evolved into a really great piece of work. I am proud of the work I've done in the past six months. I've enjoyed working on the thesis, I met some great people and I convinced myself that I am able to pull of an MSc thesis. All of this would not have been possible on my own. Therefore I would like to thank some people. For their ideas, their time and their support.

My graduation committee was crucial the development of this thesis. I thank Paulien for her spot-on feedback. Your remarks on content and structure in the meetings elevated the thesis to a higher level. I thank Igor for his extensive help with the thesis. You were the one that raised my enthusiasm for ABM in the first place and your suggestion for an evolutionary perspective on learning turned out magnificent. I thank Jill for exactly knowing what I needed in the thesis. You really helped me in making the step to the conceptual model. Your knowledge of water in Africa was amazing and above all I liked our fun conversations. We did not meet often, but when we did it was long and it was good. I thank Deirdre for making me enthusiastic about the topic. We started back in December and I like our extensive discussions about Uganda. You opened the door for me at IRC, you got me into contact with Alana, Jane, Martin, Patrick, Yared. You supported me, gave me confidence and provided me with so much feedback. You really enabled me to do this thesis.

I thank everyone at IRC for a wonderful time and an educative experience. In particular Patrick for his always honest and useful feedback and for enabling me to do this thesis at IRC. I thank Martin who helped me in so many ways and Jane and Alana for their help in the conceptualisation phase.

I thank my parents for their never ending support, however difficult the situation was at times, we can be proud of our family. I thank Jantien for her enthusiastic feedback on the thesis. I thank my room-mates and my friends, for letting me do what I do best.

I thank Yorik, for his discipline and persistence to force me to go out and train during the early months of my research. It is, even though we didn't finish at the Coolsingel the way we envisioned, an achievement to be proud of.

Karen, you helped me in ways that no one could have done. Your love and your support are heart-warming. Thank you for showing me your own struggles to distract me from mine. I am glad we went through this process together.

Words are not enough. I am happy.

Felix Knipschild

Executive Summary

In the Republic of Uganda only 65% of the population in rural areas have access to safe and clean water. Three decades ago, these numbers were even lower. The delivery of clean water in the rural areas is not improving as much as envisioned, despite the efforts of the government and other actors, resulting in Uganda not reaching her own goals, let alone international standards on water service delivery. Access to clean water services remains at 60-65% and functionality of rural water infrastructure in Uganda remains at 80-83%. On top of this worrisome current state of the water services we can observe that the speed of change in water supply sectors in general grows. It grows due to rapid advances in technology, advances in communication techniques, climate change, demographic and economic growth, raised standards of living and increased pressure on politics. The dynamics in systems grow more complex accordingly, as structures, relations and technological possibilities are evolving. Therefore we not only need to understand the current dynamics of a system, but we need to constantly evolve our understanding as the dynamics evolve likewise. A recent opportunity in research in the water supply sector is found in the ability of a sector to learn and adapt. The premise of a sector that is learning and adapting is that the sector as a whole is able to deal better with current and future challenges. A system that collectively is able to learn and adapt provides a manner to cope with the challenges.

The focus of this research is on *learning* in the Ugandan rural water supply system. *Learning is defined as the ability to recognise signals and act appropriately in response.* Within this definition individual actors can learn, for instance how to recognise valuable signals, and the system as a whole can learn, for instance what structures contribute to or hamper the spread of signals. A method to analyse both is Agent Based Modelling (ABM). In an ABM individuals act and interact according to a given set of decision-rules. This enables to conceptualise and analyse both individual acts of learning and the resulting behaviour of the system. This research explores a method to encode learning in the Ugandan rural water supply sector into an ABM and reflects on the applicability of the method to enlarge understanding of learning processes in a rural Uganda. This leads to the following research question of this thesis:

"How to conceptualise and model learning and its effect on Water Service Levels in the rural water supply sector in Uganda?"

A method to conceptualise and model learning processes in Uganda into an ABM is found in the theory of memetics. Memetics describes the evolution of information as it is transferred from person to person. The notion of a *meme*, a transferable piece of information, becomes subject of the learning processes. The argument to encode learning into an ABM with the use of memetics is as follows: first, it can help to make the abstract concept of learning more tangible. Memetics can do this by putting the focus on the subject that districts learn about. Second, the evolutionary processes that describe how a meme evolves -

selection, replication and variation - support the process of encoding learning as a clear sequence of steps is present. Third, the possibilities for memetics to encode learning processes in a multi-level governance environment in relatively unexploited. By consciously implementing memetics and consciously reflecting on the methodology this research can add to understanding of the possibilities of encoding memetics to enlarge understanding of learning processes in a water supply system.

A major challenge to encode learning processes is to develop understanding of the ways in which actors in the system of interest learn from each other. The system of interest in this thesis, rural water supply in Uganda, is characterised by an hierarchical structure where multiple institutional levels can be identified. In this thesis we look at three institutional levels: district, regional and national level. We look at how districts can learn from each other about the effectiveness of policies. Three different ways in which districts can learn from each other in rural Uganda are identified. They represent different scales of communication and they involve different institutional levels. The three structures of learning that are identified are described as follows:

Inter-district learning: a representative from a district communicates with a representative from another district. The two share their own best practices with the other and learn best practices from the other.

Regional learning: districts can share best practices and learn from each other in a variety of possibilities at regional level. Representatives from all districts in a region gather to share information.

National learning: districts can share information with each other through the Government of Uganda at national level. The national level can pick up an effective policy in one of the districts. The national level can communicate this policy to all districts by means of laws and policies that are set at national level.

The isolated effect of these structures on the performance of the water sector can be tested in the ABM using the theory of memetics. Memetics is encoded in the ABM through the processes of selection, replication and variation. The selection process is used to determine how well the meme - the policy - performs and consequently if the meme is spread to other districts. The scale of communication of the meme is determined in the replication process. In the replication process the three ways of learning as described above are represented. The variation process is used to represent the difference between districts that add variation to the policy they replicate from another district and districts that don't add variation. Experiments are performed with the Agent Based Model to research whether different methods for selection, replication and variation of the allocation ratio lead to different performance of the sector.

In conclusion modelling learning in a water supply system reveals the need to understand the concept of learning and the governance situation in the system of interest. The application of memetics evokes a discussion about the definition of performance in a sector. The replication method provides the possibility to identify learning structures in the system of interest and to observe the relation between these structures and the performance of the sector in isolation of other learning structures. Furthermore memetics provides the possibilities to analyse the effect of a conscious decision to adjust a policy to an actors own environment and what elements are needed to make this decision. This research provides policy makers with suggestions on how to consider the relation between learning in their sector and the capacity of the sector to deal with present and future uncertainty.

The efforts to encode learning processes in a system using the theory of memetics can furthermore deliver specific insights into the policy and governance framework of the system of interest. In this study for instance an argument is provided to loosen the restrictions in the allocation ratio that is attached to the budget from the Ugandan government to support the districts in delivering water services in rural areas.

Further research should focus on replication of this study. The method of encoding learning processes in a sector with memetics is promising. Replications of the research should include a heterogeneous relation between the policy that is analysed and the effect it invokes in the environment of the carriers of the policy. Research should furthermore focus on the inclusion of lower institutional levels that enable the aforementioned heterogeneous relation. Replications of this study in other systems than water can advance insights in the applicability of memetics as a method to understand learning in a system and what types of insights can be generated given characteristics of the system of interest.

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List of abbreviations

ABM	Agent Based Model
CapEx	Capital Expenditure
CapManEx	Capital Maintenance Expenditure
CAS	Complex Adaptive System
DCG	District Conditional Grant
DLG	District Local Government
DWO	District Water Office
DWSCG	District Water and Sanitation Conditional Grant
LC	Local Council
MWE	Ministry of Water and Environment
STS	Socio-Technical System
TSU	Technical Support Unit
WASH	Water, Sanitation and Hygiene
WP	Water Point

1 Introduction

In the Republic of Uganda only 65% of the population in rural areas have access to safe and clean water [Ministry of Water and Environment, 2015]. The 2009 Triple-S scoping study estimated that 35% of the rural population, an approximate 9 million Ugandans, did not have access to reliable and improved water services [Nimanya et al., 2011]. Three decades ago, these numbers were even lower. Starting with the reign of president Museveni in 1986, Uganda implemented structural policy reforms such as the decentralization of national development sub-sectors, including the water sector. The national government is administratively well organized [Government of Uganda, 1997]. The sector reforms, together with the efforts of national and local water sector actors and development partners have resulted in many practical improvements in the rural water sector. There is also a clearly defined national monitoring framework to be able to track sector performance on an annual basis [Ministry of Water and Environment, 2010, 2014, 2015].

However, the service delivery of water in the rural areas is not improving as much as envisioned, despite the efforts of the government and other actors. Uganda does not reach her own goals, let alone international standards, on water service levels. The Sustainable Development Goals developed by the United Nations state that everyone on earth should have access to safe and affordable drinking water by 2030 [UNDP, 2016]. Access to sufficient water services in rural Uganda remains at 60-65% and functionality of rural water infrastructure at 80-83% [Nimanya et al., 2011, Ministry of Water and Environment, 2010]. The progress of rural access to sufficient water services and the functionality of water infrastructure in the last six years is shown in Figure 1.1.

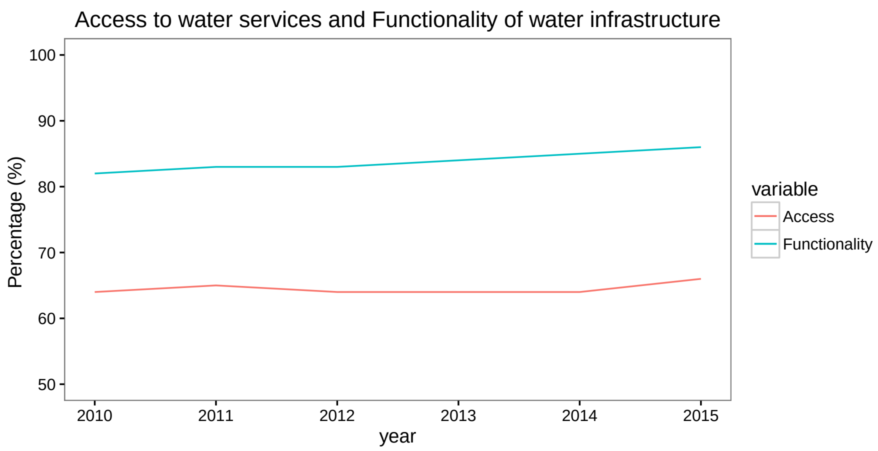


Figure 1.1. The development of access to safe water and functionality of water infrastructure in Rural Uganda from 2010 to 2015 (both shown in percentages). Data are retrieved from Directorate of Water Development and Ministry of Water and Environment [2016].

To address this situation much research has been done and many solutions are suggested [Nimanya et al., 2011]. The research field suggests improvements in, amongst others, infrastructure investments [Baguma and Loiskandl, 2010], management and maintenance of infrastructure [Carter and Ross, 2016, Nekesa and Kulanyi, 2012], organisation of the sector [Koestler, 2009, Naiga et al., 2015], technical solutions [Baguma and Loiskandl, 2010], governance and management models [Lockwood and Le Gouais, 2015, Ssozi and Danert, 2012], financial structures [Biteete et al., 2013, Matyama, 2012, Tumusiime and Njiru, 2004] and different process-driven approaches [Mirembe, 2012, Mutono et al., 2015, Quin et al., 2011] to overcome this problem. However, despite the diverse interventions, tools and approaches involved in the effort to achieve sustainable water services for all Ugandans, the rural water services *system* in Uganda is failing to achieve the vision of sustainable services for all.

1.1 A Systems Approach to Water Service Delivery

A suggestion that can possibly lead to a fundamental change in the water services sector is to approach the sector from a systems perspective. In a systems perspective we accept that delivering sustainable water services is *complex*. Modern societies are made up of complex and interlinked systems of people, institutions and technology [Lockwood et al., 2016]. In such complex and interlinked systems interactions are non-linear, meaning that we cannot easily predict the result of an intervention in the system. But more than that, we need to understand that different parts of a system are interlinked and influence each other. An intervention in a complex system can solve one issue, but can cause multiple other problems in seemingly different separate subjects in the system.

An intervention in a system that delivers *sustainable* water services is an intervention that continues to deliver services over a long period of time. An example that shows how not to deliver sustainable water services is found in a linear project approach. In a linear project approach one would identify a group of people that doesn't have access to sufficient water services and design a solution. The proposed solution is a capital investment in a piece of water infrastructure. Once constructed the infrastructure provides the group of people with sufficient water services. However, without considering the lifetime of the infrastructure, the operation of the infrastructure and minor and major maintenance of the infrastructure, it will stop delivering services within a short amount of time. A characteristic of this approach is short term planning.

In a systems perspective we would ideally identify more aspects to the solution. The water infrastructure needs to be operated by a group of people with sufficient training and sufficient motivation. Financial institutions are designed to ensure budget is available for maintenance and repairs of the water infrastructure. People with specialist knowledge are available and can be reached timely to ensure the infrastructure remains operational. This shows that we need to consider the issue of water services delivery in a broader perspective. We need to not only understand the technical possibilities, but also the social and institutional dynamics of the environment the technical solution in placed in. It is unlikely to reach a sustainable solution if the group of people with insufficient water services is considered as an isolated infrastructural problem.

The ability to understand failures and successes in water service delivery is closely connected with the ability to understand the systems complex dynamics. People and technology are intertwined in a system that is concerned with the delivery of water services. In order to deliver sustainable water services we need to understand how to work with the interaction between these two.

1.2 Scope of the Research

The speed of change in modern societies grows due to rapid advances in technology, advances in communication techniques, climate change, demographic and economic growth, raised standards of living and increased pressure on politics [Lockwood et al., 2016]. Complex dynamics in a system, described in section 1.1, grow accordingly as structures, relations and technological possibilities are evolving. Therefore we not only need to understand the current dynamics of a system, but we need to constantly evolve our understanding as the dynamics evolve likewise. Unravelling the dynamics in a system cannot be done by one actor, as multiple actors, their goals, actions and interactions form the dynamics of the system. Multiple people, organisations, and academics need to bundle efforts to spread understanding through the system. Furthermore, there would ideally be lasting structures in the system that constantly evaluate and enlarge understanding of the evolving dynamics.

A recent discussion in the Water, Sanitation and Hygiene (WASH) sector is about the ability of a sector to *learn and adapt* [Da Silva Wells et al., 2013, IRC-Uganda, 2014, Lockwood and Smits, 2011, Da Silva Wells and Casella, 2014, Mirembe, 2012, Van Soest et al., 2015, Robinson et al., 2010]. The premise of sector learning and adapting is that the sector as a whole is able to deal better with current and future challenges [Da Silva Wells and Casella, 2014]. If we assume uncertain future dynamics in a system and if we assume that predicting the dynamics well is at the least very difficult, then we can try to adapt the structures in the system that enable us to constantly evolve our understanding of the systems dynamics. A system that collectively is able to learn and adapt provides a manner to prepare for uncertainties in the future.

The premise of the advantages of a system that is able to learn and adapt might be clear, however, insights in how learning and adapting can contribute to progress on water service levels in a water system lacks. Questions remain regarding learning in a system: who is able to learn in a system? What do they learn about? What structures need to be in place for learning? Who facilitates learning structures in a system?

The focus of this research is on *learning* in a system that delivers water services. Learning in this thesis is not considered to be textbook learning or the acquirement of new skills. Instead, the thesis is focussed on the spread of information through a system. I am interested in the structures in a system that are suited to effectively spread evolving understanding.

Learning is defined as the ability to recognise signals and act appropriately in response

Learning provides the opportunities to constantly understand the relations between different parts of the system. I assume that better understanding results in more effective policy making and more effective use of resources. Learning itself, however, may also not be considered in isolation. We are always learning about something, be it the use of technology or the more effective implementation of community management models.

1.3 Research Questions, Research Objective and Research Methodology

In a water supply system technical artefacts, e.g. water infrastructure, are strongly interrelated with a social network of people and organisations that make decisions about the water infrastructure. The system is governed: it is bounded by rules, regulation, law, social norms and culture. However, within these boundaries, and to a certain extent outside of the boundaries, every person, each organisation, every decision-making entity, has the opportunity to shape the behaviour of the system. The observed system behaviour is a function of the actions of all individuals that act and interact within the system boundaries.

There are two different concepts of learning in a system. First, **individual actors** in a system can learn how to spread information and policies to other actors in the system. These actors also learn how to recognise opportunities to learn useful information or an effective policy and the individual actors can learn when and how to act appropriately upon valuable information. Second, the **system**, the collective of actors and institutions, can learn what structures can contribute to or hamper the effective spread of information and policies across the system.

Given the previous two paragraphs, we can say that we are interested in both individual acts of learning and the collective behaviour resulting from processes of learning in the system. A method to analyse both is Agent Based Modelling (ABM). In an ABM individuals, or *agents*, act and interact according to a given set of decision-rules. From the result of all agent interaction in an ABM we can observe behaviour of the system. The behaviour is called emergent, because it is not a pre-defined behaviour of the system, but rather the result of a process of interactions. In an ABM we are able to conceptualise and analyse both individual acts of learning and the resulting behaviour of the system.

In this chapter I showed that the focus of this thesis is on understanding of learning processes in the rural water supply sector in Uganda. The learning processes are not analysed in isolation. I am interested in the relation between learning in the sector and the performance of the sector. In rural Uganda the performance indicators that are used are the *water service levels* [Biteete et al., 2013]. Water service levels include amongst others indicators for water quality, water quantity, reliability and accessibility of the services. From all the previous we can distil the following research question:

"How to conceptualise and model learning and its effect on Water Service Levels in the rural water supply sector in Uganda?"

Answering this research question serves another goal. Previously in this chapter we have seen that the system is failing to achieve universal coverage in rural Uganda and that there is little progress towards Sustainable Development Goals. In section 1.1 the premise of a systems perspective is described and in section 1.2 the role of a learning and adapting sector is described. I aim to help both the research community and the people and organisations that work in the sector with this research. I want to create insights in the role of learning to reach higher water service levels in the sector and want to show if a systems perspective can help in achieving this goal. Therefore I formulated a research objective:

Help both the research community and those who work in the Ugandan rural water supply sector to enlarge understanding of the role of learning on progress on water service levels in the sector from a systems perspective.

This is the outline of the thesis. In chapter 2 we go into learning. First the role of learning and adapting in a socio-technical system is explored. The emphasis is on the role of learning as a way to cope with increasingly uncertain dynamics in a system. Thereby we approach the system as a *socio-technical system*. Next, this chapter decomposes the concept of learning. We have seen that individual actors can learn and that we can observe learning in the system as a whole. But who are the individual actors that learn? What do they learn about? And how do they learn? The sub-question that is answered in this chapter is as follows:

How can learning be decomposed to understand the spread and uptake of information in a Socio-Technical System?

In chapter 3 we turn to the rural water supply sector in Uganda. First, a description of the actors and the institutions in the sector is given. A financial case study is used to understand the spread of information in the sector. After that we see how learning as it is decomposed in the previous chapter is applied to the financial case study in rural Uganda. Next, an analytical framework is presented. In the framework the sector is presented as a Socio-Technical System. In the final part of the chapter the sector is described in terms of a Complex Adaptive System and the possibilities of analysing learning in the sector with an Agent-Based Model (ABM) are explored. The sub-question that is answered in this chapter is:

How can a conceptual model of learning in the Ugandan Rural Water Supply Sector be made?

In chapter 4 the first step of the modelling cycle for ABM is described. The thesis goes through model conceptualisation, specification, experimentation and validation as are described in Dam et al. [2013]. In the chapter a conceptualisation is provided of the financial case study in rural Uganda as well as a conceptualisation of learning processes in the case study. The chapter shows a conceptual model of what is analysed in the ABM and explains the assumptions and abstractions that are needed to construct the ABM. In the specification in chapter 5 the conceptualisation phase is further refined. The specification phase identifies the agents in the model and describes what they can do, what they have and how they behave. In a model narrative the procedures in the ABM are explained. The set of assumptions is described in further detail, creating the possibility to encode the model narrative in an ABM. Next, in this chapter the verification steps are described, showing that implementation of the code is actually producing the actions and interactions that are described in the conceptual model. In chapter 4 and chapter 5 together, the following sub-question is answered:

What assumptions, boundaries and inputs are incorporated in the ABM?

Next, in chapter 6, the experiments that are performed with the ABM are described. In the experiments the behaviour of the system that is produced by the ABM under different sets of inputs, the experiments, is described. This chapter describes why and how the experiments are set up, leading to the following sub-question:

How is experimented with the ABM?

After the experimental design in chapter 6, the results of the experiments are shown and analysed in chapter 7. In this chapter visualisations are shown, representing the outcomes of the different experiments produced by the ABM. The experiments explore the effect of different structures of learning in the rural water supply sector in Uganda.

In the first part of the thesis the concept of learning is decomposed and applied to a specific environment: rural water supply in Uganda. Social learning is encoded in an ABM and experiments are performed to explore different scenarios for social learning. In the validation in chapter 8 we validate if the model produces behaviour that is realistic and we reflect on the behaviour generated by the ABM with multiple system experts. The following sub-question is answered:

How valid is the observed behaviour in the ABM in reality?

In chapter 9 conclusions of the thesis are represented. The conclusions reflect on the methodology that is used to implement learning in an ABM and on the specific insights that are generated for the case study in rural Uganda. The chapter furthermore discusses limitations and directions for future research.

2 | Learning and Adapting in a Socio-Technical System

In this chapter a theoretical background on learning and adapting in a Socio-Technical System (STS) is provided. Policy makers in STS operate in an increasingly dynamic environment. In this thesis we look for a way to conceptualise and ultimately model learning in a specific multi-level governance environment: rural water supply in Uganda. At this point we need to understand in what way learning influences the behaviour of a system and we need to understand how learning can occur in these systems. In section 2.1 the necessity of learning processes in an STS and the theoretical handles for a policy maker are described. Next, in section 2.2 we go into learning in an STS. We need to understand learning in systems with multiple levels of governance to be ultimately able to model learning in rural Uganda. The section decomposes learning into more tangible pieces.

2.1 The Necessity of Learning in a Socio-Technical System

One of the characteristics of a Socio-Technical System (STS) is uncertainty in the future state of the system. The uncertainty is caused by the coupling of social and technological elements. The interactions between these elements are unpredictable [Wilson, 2002]. Social systems continuously change. The scale of organisation in a social system might shift and besides uncertainty about the future state of a STS, also the current understanding of the system is likely to be wrong [Dietz et al., 2003]. Gunderson and Holling [2002, ch. 2] argue that uncertainty increases in times of abrupt or disorganising change. In these periods of change, the dynamics of the system are unclear, the experience of actors is incomplete for understanding the dynamics and the consequences of their actions on the dynamics are unclear [Gunderson and Holling, 2002, pp. 17]. Steffen et al. [2004] add that periods of abrupt change are expected to increase in frequency, duration and magnitude.

Adaptive management provides a means to deal with uncertainty in a STS [Folke et al., 2005, Dietz et al., 2003]. An underlying assumption for adaptive management is that policy makers accept that there is uncertainty in the system and accept their impotence to predict the future state of the system. In adaptive management a policy can be observed as an hypothesis of how the system works. Every management action is a way to test this hypothesis [Gunderson et al., 1995]. In this perspective, each management action is used as an opportunity to learn how to adapt to changing circumstances in the system [Carpenter and Gunderson, 2001]. According to Gunderson and Holling [2002] a principal lesson for adaptive management is that policies may be suboptimal in the short run, but can be wiser in the long run.

The extent to which actors in a system can adapt to change influences the *resilience* of a system. Walker et al. [2004, pp. 2] define resilience as *"the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity and feedbacks"*. The capacity of the actors in a system to influence the resilience of a system is called *adaptability* [Berkes et al., 2003, Walker et al., 2004]. This capacity is influenced by the collective of individual actions by the actors in the system. Olsson et al. [2004a] argue that in periods of abrupt change in a SES, the capacity of actors in a system to keep the system in a desired state is reduced. Resilience can be either desired or undesired, depending on the viewpoint of the actors. In turn, the viewpoints of the actors can also be different, because they have different goals and different information about the state of a system.

Closely connected to the domains of resilience and adaptive management is the concept of *adaptive governance*. Adaptive governance is best applicable in systems that are characterised by complexity and uncertainty [Chaffin and Gunderson, 2016, Folke et al., 2005, Dietz et al., 2003]. Governance includes the structures and processes that steer human behaviour in a system [Pierre, 2000]. The extent to which governance is adaptive depends on the flexibility of the structures and processes and how easy or difficult it is for actors to change them. This relates to adaptive management as it is concerned with the testing of different structures and policies to enable the system to deal with uncertainties and limited knowledge. Moreover, Dietz et al. [2003] argue that adaptive governance is used to *expand* the concept of adaptive management by including a broader social context.

In both adaptive governance and adaptive management the ability of actors to self-organise plays an important role. Processes of self-organisation can emerge into systems of *adaptive co-management* [Ruitenbeek and Cartier, 2001, Olsson et al., 2004b]. Folke et al. [2005, pp. 439] describe adaptive co-management as *"a process by which institutional arrangements and ecological knowledge are tested and revised in a dynamic, ongoing, self-organized process of learning by doing."* In the same article, the role of the social context in the emergence of adaptive co-management is emphasized, by describing the roles of networks, leadership, social capital and trust [Folke et al., 2005].

In this section we have seen multiple concepts that describe the relation between the actors in a system and uncertainty in a system. Increased pressure on social and technological element emphasises the need for a system that is able to learn and adapt. We have seen that different structures in the system can foster or hamper adaptability of the system. Ultimately, all different concepts and theories that are described deliver insights to policy makers in how to deal with increasing uncertainty in an STS.

2.2 Decomposing Learning in a Multi-level Governance Environment

Adaptive management can be enhanced when actors become more adaptive by effectively learning from their experiences. Fazey et al. [2005] state that learning is an important part to permit good adaptive management, by building skills and knowledge into organisations and institutions. Folke et al. [2005] add that learning can help to develop expertise which is an essential feature for governing, as it can prepare decision-makers for uncertainty and surprise. Learning also adds to the resilience of a sector, by making individual actors more able to adapt to change and thereby increasing the cumulative adaptability of actors in the system [Folke et al., 2003]. Kaspersma [2013] describes three different schools of thought about learning:

1. *behaviourism* describes learning as a mechanism, a behavioural response to some sort of stimulus;
2. in *cognitive sciences* learning is the absorption of information from the environment, mentally sorting it and applying it to every day activities; and
3. the school of *experiential learning* describes learning as a process of translating experiences into knowledge.

The process of learning in an STS is often referred to as *social learning* [Lee, 1993, Clark et al., 2001, Ison and Watson, 2007, Jiggins et al., 2007], or *institutional learning* [Ostrom, 2005]. Social learning is a theory that bridges the gap between the behaviourist perspective and the cognitive perspective on learning, as is includes attention, memory and motivation [McLeod, 2011]. The three latter describe how a stimulus in the behaviourist perspective is interpreted in the cognitive perspective. According to Bandura and Walters [1963] the theory of social learning explains human behaviour in terms of reciprocal interaction between cognitive, behavioural, and environmental influences, thereby arguing that learning is not purely behavioural, but also a cognitive process occurring within a social context. Bandura and Walters [1963] furthermore argue that one can learn by observing a behaviour, but also by observing the consequences of the behaviour. The actual learning occurs when information is extracted from those observations, enabling one to make a conscious decision about the observed performance.

Observing the different perspectives on learning does not yet tell us who are learning in an STS, what they are learning and how they are learning about it. An analysis of the three follows in the following subsections.

2.2.1 Who Learns?

Multiple stakeholders at multiple institutional levels in a system as well as the system itself are able to learn. Kaspersma [2013] considers three different levels in a system and argue that these levels are *nested* in each other. An individual can learn and is embedded in an organisation that, in turn, can learn as well. The organisation is embedded in an institutional environment that is also able to learn. The institutional environment is the broader context where the organisation (and the individual) operate in and can be expressed in policies, political climate and civil society.

Although all stakeholders in a system are able to learn, Fabricius and Cundill [2014] argue that it is mostly research scientists and managers that are concerned with the deliberate effort to learn about learning in resource management systems. There is very little public participation in efforts to foster learning in adaptive management.

2.2.2 What do they Learn?

Actors in a system can learn about different types of knowledge. Kaspersma [2013, pp. 41-42] describes four different competences that can be acted and learned upon:

Technical competence: concerned with analysing and solving a problem of a technical nature.

Management competence: concerned with the need for an adequate pool of resources across the three levels mentioned before (individual, organisation, system).

Governance competence: concerned with the ability to foster and apply principles of good governance.

Competence for continuous learning and innovation: a meta-competence, applicable to each of the previous competences, concerned with the deliberate efforts to learn and innovate.

The first three competences can be learned upon by experience and practice, while the fourth competence is monitoring and developing the other competences. The fourth competence describes the deliberate process to learn faster about the other competences. This understanding adds to the identification of *who* is learning, as every stakeholder in a system learns from their experiences (e.g. they act and interact in an environment, receive feedback from their actions, encounter new situations), but a few of them are involved in the efforts to learn about how to learn. An example of actors concerned with the competence for continuous learning and innovation are the aforementioned resource scientists and managers [Fabricius and Cundill, 2014].

The competences that are not concerned with the deliberate efforts of how to learn - the technical, management and governance competences - can be made more explicit by applying them to the level of the individual. Kaspersma [2013, p. 93] argues that the competences can be delineated into four components:

a cognitive-explicit component: concerned with the use of information or objective and replicable theory;

an informal-cognitive component: concerned with the knowledge gathered by experience of an individual;

a functional component: concerned with the skills related to the tasks of an individual; and

a personal component: concerned with an individuals attitude in a specific situation with specific personal and professional values.

Loop-learning is a theory that describes what actors can learn. The theory of single-loop and double-loop learning is based on the experiential perspective on learning. The method shows cycles between actions and feedback from actions. The theory is first introduced by Argyris [1976] in the field of organisational decision-making. In single-loop learning a connection between the strategy for an action and the result of that action is made: a decision maker observes the results, uses the feedback, and adjust the strategy. This can be seen as the basic form of problem solving.

The second loop of learning is normally reached when single-loop learning proves insufficient. Double-loop learning calls for a revision of underlying strategies and goals in order to solve a problem. Argyris [1976] argues that double-loop learning occurs in times of extreme crisis and revolution. In organisational theory double-loop learning is used to explain social phenomena in team-building and in inter-cultural settings.

Fabricius and Cundill [2014] argue that neither single-loop learning nor double-loop learning is better in the management of a system, but that a combination of the both is needed. Single-loop learning is essential to make progress in the management of natural resources in a complex system, where double-loop learning is essential for innovation and critical appraisal. For instance, a system where stakeholders only use double-loop learning would only 'learn how to learn', without making any advances in practice.

Triple-loop learning, an extension of the single-loop and double-loop learning theory, is also originated in organisational theory and is based on experiential learning. The concept is first introduced by Hargrove [2002] and refers to an adjustment of values and beliefs in a decision-making process. The third loop *refers to a transformation of the structural context and factors that determine the frame of reference* [Pahl-Wostl, 2009, p. 359].

2.2.3 How do they Learn?

So far in this chapter, we have seen a number of perspectives on learning and social learning. Different perspectives represent different conceptions of how one is able to learn. From the perspective of behaviourism, we learn by recognising a pattern in situation, behaviour and reward. The cognitive perspective emphasises the mental process of sorting observed information and applying it in different situation. In the theory of social learning one should observe learning as a combination of behaviourism and cognitive learning aspects, within a social context. The three elements are mutually influencing each other.

Another perspective that describes learning is found in the theory of *memetics* [Dawkins, 2006]. Memetics describes how a piece of information is transferred between people and evolves in the process of being transferred. An interesting observation is that the subject changed: the people that were learning are no longer the subject, but the piece of information that is transferred between people is the subject of learning processes. In this sense the people that encounter the piece of information are carriers that influence the information: they add data to it, they change the information according to their own perception or they can do nothing with the information, therewith stopping the evolution of that particular piece of information.

Memetics theory states that human condition is influenced by at least two selective processes: biological (genetics) and social (memetics) [Marsden, 1998]. The necessary conditions for the loop of evolution - replication, variation and selection - are present in both processes. These processes act on - i.e. they replicate, variate and select - a similar subject: the gene in genetics, the *meme* in memetics. A gene can be understood as a unit of biological information and a meme can be understood as a unit of cultural information [Heylighen and Chielens, 2009]. Cultural traits are transferred from person to person and in that process the cultural trait, the meme, is subject to processes of replication, variation and selection. A meme can be defined as an information pattern that is held inside the memory of a person, and which can be copied to the memory of another individual [Heylighen and Chielens, 2009].

To understand the process of cultural evolution from the perspective of a meme consider the following [Heylighen and Chielens, 2009]: memes can differ in their degree of fitness to their environment, i.e. they are or are not sufficiently adapted to the socio-cultural environment in which they propagate. Fitter memes are likely to be successfully communicated more often than less fitter means, resulting in a larger spread over a population.

An example of memetics as a form of social learning is provided by a songbird experiment [Lynch, 1996]. In this research a song is transferred from generation to generation via processes of social learning.

Two basic requirements in the evolution of the *songs*, variability and heritability, allow us to observe development of songs in bird species as processes of cultural evolution.

2.3 Towards Encoding Learning in a Multi-Level Governance Environment

In this chapter we have seen multiple concepts that describe the relation between the actors in a system and uncertainty in a system. The relevance of learning is explained by the coupling of social and technological elements that is a characteristic of STS. Increased pressure on both elements emphasises the need for a system that is able to learn and adapt. A higher speed of change in a system calls for higher adaptability of the system, which is formed by the cumulative capacity of actors to change the system. We have seen that different structures in the system can foster or hamper adaptability of the system and we have seen that you can measure the severity of a crisis that is needed to significantly change a system is measured by the resilience of a system. Resilience and whether or not the system is in a favourable state, however, is subject of debate due to the many different stakes of the actors that are part of the system. Ultimately, all different concepts and theories that are described deliver insights to policy makers in how to deal with increasing uncertainty in an STS.

Furthermore, in this chapter we have seen a decomposition of learning in a multi-level governance environment. The concept of learning is complex and there are multiple thoughts on how learning processes occur, represented by different perspectives on learning such as the behaviourist, the cognitive and the experiential perspective. We have seen that learning processes are observed at different organisational scales: from an individual, to an organisation to a complete system. These actors can learn about four different competences: technical, management, governance and learning. Different *loops* of learning can be considered when analysing what the actors learn in different magnitudes of the challenge. Descriptions of how actors learn are provided by the different perspectives on learning. The theory of memetics provides a different perspective on how learning occurs in a system. It describes how a piece of information evolves using actors, rather than the actors learning themselves.

However, we are still looking for a way to encode learning processes into an Agent-Based Model (ABM). An example of a study where social learning is implemented in a modelling study is given by Pahl-Wostl [2002]. In this study participatory approaches and analytical modelling using ABM are combined to explore changes towards sustainable technological regimes and institutional settings. In Pahl-Wostl et al. [2007] social learning is described as a method to escape lock-in, where actors need to learn their own frames of reference and how these influence or restrain their thinking, as well as the fact that other actors can have other frames of reference that are legitimate. In the paper, social learning is assumed to occur at two levels [Pahl-Wostl et al., 2007, p. 10]:

1. at short to medium time scales, at the level of processes between actors; and
2. at medium to long time scales, at the level at which the governance structure is shifted.

Considering the research question of this thesis we look for a way to conceptualise and ultimately model learning in a specific multi-level governance environment: rural water supply in Uganda. At this point we are able to understand in what way learning influences the behaviour of a system and we understand many different perspectives on how learning can occur in these systems. However, ways to encode learning in order to model and simulate learning in the rural water supply sector in Uganda still lacks. We first turn to Uganda in chapter 3. The chapter describes the system in Uganda, including a case study that is used for modelling purposes (section 3.2). The application of *learning* on the case study is provided after that and is described in section 3.3. The concept of learning in rural water supply Uganda that is described there provides sufficient handles to encode the model and finally perform experiments with the model.

3 | The Rural Water Supply System in Uganda

In this chapter the rural water supply system in Uganda is central. Remember that we are looking for methods to conceptualise and model learning in this particular sector. In chapter 2 the need for learning in an STS is described and understanding of learning in such a system is enlarged by decomposing the components. First the sector is described and positioned as a multi-level governance environment in section 3.1. Multiple institutional levels are identified and their roles in rural water service delivery are described. Next, in section 3.2, a type of financial allocation in the sector is introduced. The case is about financial resource management of the districts in Uganda. We use the case to model a demarcated situation where we can observe learning processes and analyse the method used to encode them. Thereafter, the decomposition of learning in section 2.2 is applied to the financial case in section 3.3. This section describes which actors in the financial allocation case of rural Uganda learn, what they learn and how we envision they learn about it. The process of conceptualising and encoding learning in the ABM is further described in chapter 4 and chapter 5. After an extensive description of the case study two perspectives on rural Uganda are provided: rural Uganda as an STS in section 3.4 and rural Uganda as a Complex Adaptive System (CAS) in section 3.5. Rural Uganda is firstly positioned as an STS to understand the uncertainty in the system caused by the coupling of social and technical element and to understand why learning processes as they are decomposed in the previous chapter are important. Rural Uganda is secondly positioned as a CAS to make a connection to a modelling technique: Agent Based Modelling.

3.1 Multi-Level Governance

Uganda, a landlocked country in Sub-Saharan Africa, has a population of approximately 37 million people, of which about 83% live in rural areas [Trading Economics, 2015]. In 1997 the Government of Uganda started a process of decentralisation. These efforts have resulted in formal structures and responsibilities across different sectors, the water sector amongst others [Government of Uganda, 1997]. Decision-making in the sector is dispersed from village level to national level and can be described by the concept of *multi-level governance*. This means that the efforts to provide water services to the rural population are observed at multiple institutional levels. Uganda is divided in multiple regions that each consist of multiple districts. The total number of districts is 111. The districts consist of counties and those are divided into sub-counties. The sub-counties consist of villages, parishes and communities.

At national level the Ministry of Water and Environment (MWE) is responsible for the rational and sustainable utilisation, development and management of water resources [Ministry of Water and Environment, 2013b]. The MWE is responsible for regulating water resources, setting national policies and standards, and determining priorities for water resource management [Ministry of Water and Environment, 2013b, p. 10]. There are three directorates in the MWE, including the Directorate of Water Development that is concerned with the technical oversight in planning and implementation of the delivery of rural water services. The rural water supply sector is financially intensive and much financial support is derived from national level by the Ministry of Finance, Planning and Economic Development.

There are multiple interpretations of regions in Uganda. A district can for instance be in multiple regions, depending on the purpose of the region. There are regional WASH-alliances – such as the Rhwenzori WASH alliance – and regional learning fora. At these alliances and fora representatives from districts come together to share experiences with each other. Another demarcation of the region is provided by the Technical Support Units (TSU). There are 8 TSUs in Uganda, each covering a region ranging from 8 to 20 districts. A TSU supports capacity building at district level, including training, technical advice and technical support [Ministry of Water and Environment, 2013b, p. 12]. The TSUs cooperate closely with the MWE at national level. In the sector they are seen as *the eyes of the government*: they monitor progress in the sector, they identify best practices and they control adherence of the districts to national policies [Nabunnya et al., 2016].

In each of the 111 districts a District Local Government (DLG) is present. The DLG is responsible for the planning and implementation of water activities for the communities living in the district [Ministry of Water and Environment, 2013b, p. 13]. The District Water Office (DWO) is the party that takes the lead in implementing rural water activities in the district. The role of the DWO is practical, such as contract management, ensuring operation and maintenance, and monitoring the water infrastructure in the district. The District Water Officer is the chief of the DWO. The Chief Administrator Officer is responsible for the overall management of the water activities in the districts and is the accounting officer of all district funds that are available for water activities [Ministry of Water and Environment, 2013b, p. 14]. The Local Council (LC) is an elected government that operates at district level. There are multiple hierarchical levels within the council: from LC1 – responsible for villages – to LC5 – responsible for the whole district. An idea or a problem at village level can be relayed up to district level through the LC. The LC is not able to convey messages directly up to national level, on paper this communication line is via the DLG. Hand pump mechanics are gathered in a Hand Pump Mechanics Association that operates at district level. The mechanics repair broken infrastructure and install new infrastructure.

At (sub-)county level the Sub County Water and Sanitation Coordination Committees fill in the gap between district level and parish level. The Committees play a role in monitoring and coordinating water activities at the level where they are implemented [Mirembe, 2011]. Hand pump mechanics are usually active in one or more counties within a district. The water service committees are representatives from the communities. They are responsible for day-to-day operations of the water infrastructure: money collection, maintenance and administration [Lockwood and Smits, 2011]. Development partners operate at every level and help to reach higher water service levels in different ways, such as direct support, training, and advocacy. An overview showing multiple governance levels in the sector is show in Figure 3.1.

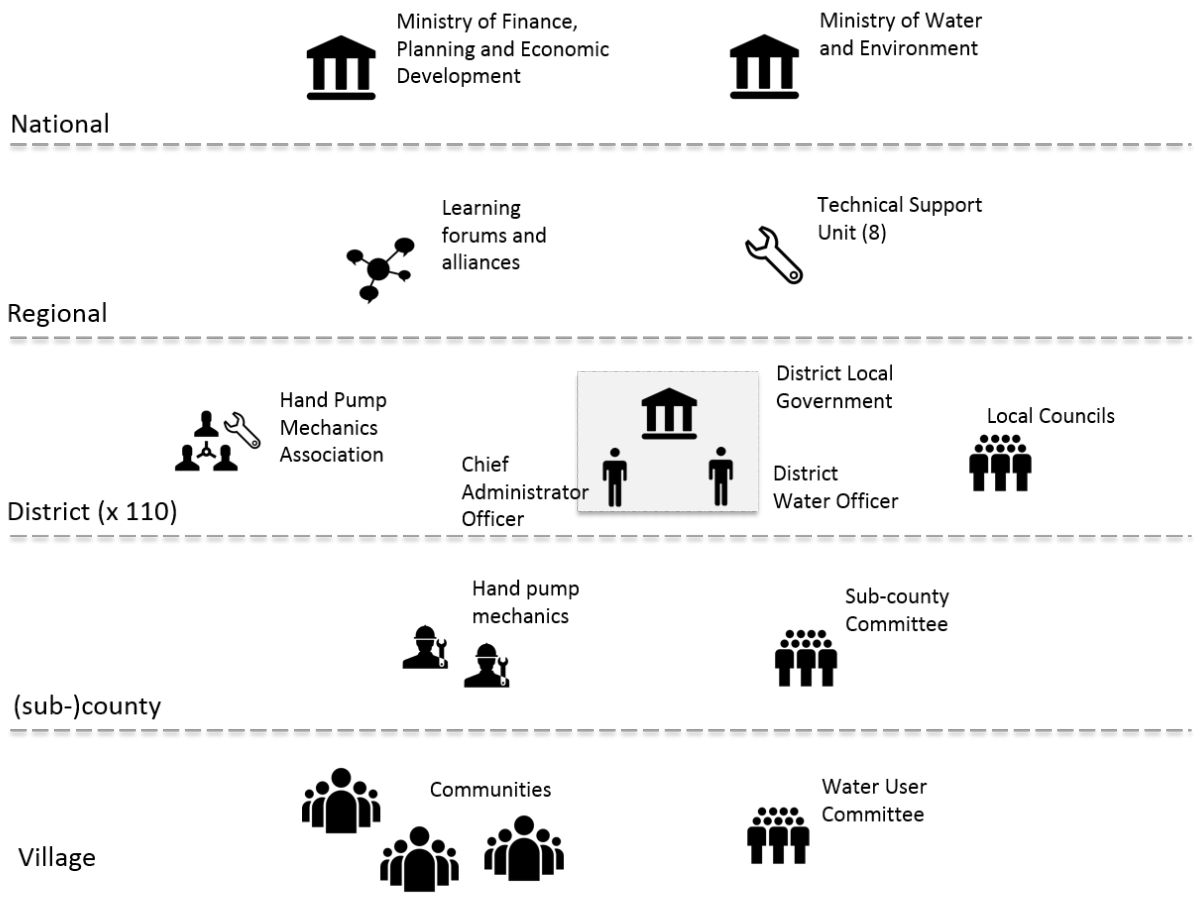


Figure 3.1. Multi-level governance in Rural Uganda. At the least five difference levels of governance can be identified in rural Uganda. All levels are concerned with the delivery of Water Services to the rural Ugandan population. The figure is adopted from Van Tongeren [2014, p. 24] and modified for this thesis.

3.2 Financial Allocation

In order to be able to conceptualise *learning* in the rural water supply system in Uganda a financial allocation case is described. We want to identify *something* that can be learned by *someone* and explore different scenarios of how the learning takes place. The financial case enables us to do so. First, a piece of information, a *meme*, is identified in the Ugandan water supply system. The concept of a meme is described in subsection 2.2.3. Next, actors that are able to transfer and learn about the meme are identified and described, therewith a choice is made to focus the analysis on certain institutional levels.

In the financial resource allocation case there are multiple institutional levels involved. In Uganda the DWO at district level receives financial support from the Government of Uganda at national level for investments in water infrastructure. The budget is provided to the district by means of a District Water and Sanitation Conditional Grant (DWSCG) that is allocated by the Ministry of Finance, Planning and Economic Development via the MWE to the District Local Governments [Ministry of Water and Environment, 2013a].

The Directorate of Water Development, the department of the Ministry responsible for regulating and managing the water sources in the country, decides on an *allocation ratio*. The allocation ratio dictates what the budget in the DWSCG should be spent on by the districts. It dictates what part of the DWSCG is to be spent on new infrastructure - Capital Expenditure (CapEx) - and what part may be spent on various forms of direct support, such as Operation & maintenance, Operational Expenditure and Capital maintenance expenditure (CapManEx). The Directorate of Water Development at national level decides on the conditions in the ratio, as well as on the formula that determines how much money is allocated to each district. The District Local Government at district level should spent the budget according to the conditions specified in the DWSCG.

District level, consequently, has the mandate to decide on what locations to spend the budget, as long as it is spent according to the conditions that are set by the Directorate of Water Development. An example to show the task of the District Water Office is provided by Kabarole district. In Kabarole district there are over 1200 water service committees that are responsible for one or more water points of any kind [Boulenouar, 2014]. The District Water Office has the task to divide the budget between those 1200 water service committees and potential new water infrastructure.

The Water and Sanitation District Conditional Grant

Every year, the District Water Offices (DWO) at district level draft a *work plan*. This plan serves as a funding request to the Government of Uganda. In the work plan the DWO describes on what projects it will spent what amount of money in the following year. The DWO specifies the financial support they need from the national government to fulfil their task. National level obliged the DWO to include monitoring results of the progress of the work plan of last year from the districts [Ministry of Water and Environment, 2012]. The district prepare their work plan between February and May.

The work plans are evaluated at national level in May and June. If the budget in the work plan exceeds the allocation budget ceiling for the district, the plan has to be revised between mid-June and end-June by the DWO [Ministry of Water and Environment, 2012, p. 7]. The final submission of the Work Plan is then directly done by the MWE to the Ministry of Finance, Planning and Economic Development. Next, the MWE can decide to lower the budget that is provided to the district on a number of reasons, including a feasibility assessment and an assessment of previous evaluations of work plans from the district [Ministry of Water and Environment, 2012, p. 15]. If an activity is delayed into the next financial year, the activity has to be paid from the budget of the next financial year, together with budget that is planned but not spent yet [Ministry of Water and Environment, 2012, p. 5].

Currently, the DWSCG formula to determine the ceiling of the budget expenditure that each districts receives consists of three parts [Ministry of Water and Environment, 2013a]:

1. budget to cover expenses of the District Water Office;
2. a condition to ensure there is budget for minimum basic investments; and
3. budget to reach the average level of national coverage in a district within 5 years.

This formula aims to erase inequality between districts in Uganda. The formula translates the rationale of national government to help the unserved people in the districts that are below national average first. The decision is based on coverage numbers: those communities that are not *covered* should receive the most attention. This rationale is represented in the third condition: districts that are performing below average are funded to reach the average national coverage within a period of 5 years. Districts that perform above average, however, are not stimulated by the formula to reach higher coverage for the people in their district. Districts that perform above average would *ideally* receive zero allocation according to the description that is added in the formula documentation, but this would be *unacceptable* [Ministry of Water and Environment, 2013a, p. 1]. Condition 2 ensures there is some budget for minimum basic investments for every district, including those that perform above national average.

The target of national government that is used to calculate the budget ceiling a district can receive in a year is the average national coverage. This leads to a number of interesting observations. First, districts with coverage below the average national coverage are encouraged to reach the national coverage in 5 years time. The national coverage is approximately 65%. When this policy is successful, the districts reach a coverage of 65% in 5 years time. The second observation is that districts with a coverage similar or higher than the average national coverage would receive zero or less budget if the second condition is absent. The formula is not explicit about the *budget for minimum basic investments*. It is not clear if a district is able to maintain the current coverage percentage using the budget for minimum basic investments, if a district can improve coverage with the budget or if the coverage in districts slowly aggregates to the average national coverage and the budget the districts receive is only for public acceptance. Regardless of the goal of the budget for minimum basic investments, the districts that perform well receive a disincentive from national government via the formula in the DWSCG to report that they are performing well.

The budget is only released to the district if it signs to adhere to the following conditions [Ministry of Water and Environment, 2012, p. 14]:

(a) *"Rural Water Supply Facilities not less than 70% of the total budget.*

(b) *Software activities for rural water supply and sanitation up to 8% of the total budget.*

(c) *Rehabilitation of boreholes and Piped water schemes up to 13% of the total budget.*

(d) *Construction of sanitation facilities up to 3% of the total budget.*

(e) *Supervision, monitoring and DWO operational costs up to 6% of the total budget."*

We can make some observations when we analyse these conditions. From condition (a) we can derive that the majority of the budget is to be spent on new infrastructure. Furthermore, the budget for sanitation in the DWSCG is much less than for water as can be deducted from condition (b) and condition (d). Condition (b) is the equivalent of *indirect support* and condition (e) is the equivalent of *direct support*, according to the life-cycle costing framework that is provided in Table 3.1.

In this section we have seen a description of a financial allocation case in rural Uganda. We have seen what actors are involved in the case and that the interactions between the actors are mainly between the national institutional level and the district level. Furthermore, we have seen a description of how the budget is allocated from the national level to the district level and that the actor at national level provides conditions with the allocated budget that dictates the district level what to spend the budget on. In the next section we define how we can observe learning processes in this financial allocation case.

Cost Category	Explanation
Capital expenditure (CapEx)	Expenditure on fixed assets such as physical infrastructure (for initial construction or system extension), and the accompanying 'software' such as capacity-building.
Operating and minor maintenance expenditure (OpEx)	Expenditure on labour and materials needed for routine maintenance which is needed to keep systems running, but does not include major repairs.
Capital maintenance expenditure (CapManEx)	Renewal, replacement and rehabilitation costs which go beyond routine maintenance.
Expenditure on direct support	Costs of ongoing support to users and local stakeholders, for example on local government or district support staff.
Expenditure on indirect support	Costs of higher-level support, such as government planning, policy-making and regulation.
Cost of capital	Costs of servicing capital such as repayment of loans

Table 3.1. Life-cycle cost components of water infrastructure, adopted from Fonseca et al. [2011]

3.3 Analysis of Learning in the Financial Allocation Case

This part describes how *learning* can be understood and analysed in the financial case. In section 2.2 learning in an STS is decomposed into different parts. In this section the decomposition is used and applied to the rural water supply sector in Uganda and more specifically to the financial case as is described in section 3.2. This will add to our understanding of learning processes and furthermore, enables to conceptualise learning in this system. This section describes what actors learn in the financial case, what the actors learn and how they learn about it.

What actors learn? In the financial allocation case the Directorate of Water Development at national level dictates what the districts spend their budget on. For instance, at least 70% must be spent on new infrastructure - CapEx - and only a maximum of 13% may be spent on maintenance that goes beyond routine maintenance - CapManEx. The districts have some room for manoeuvre in how they use the final allocation ratio. Every year, a district must choose on what projects they spent the budget. In the work plan a districts files to the ministry the projects and budgets needed for the projects are stipulated. A District Water Office (DWO) can manoeuvre in the allocation ratio in the choice of projects it files to national level. This results in the conclusion that district level is the most interesting level in the financial case study to observe learning processes at, because the actors at district level can learn how use the room for manoeuvre in the allocation ratio to reach higher water service levels. The districts learn the relation between an implementation of an allocation ratio and the water service levels in their district.

What do the districts learn? The DWO *learns* how an allocation ratio affects the water service levels in the district. The DWO are obliged by the MWE to monitor the status of the water infrastructure in the district and the performance of the last year. The way the districts decide to spent the budget results in a change in water service levels. District level can experiment with different resource allocation ratios. They gradually experience what ratio works best in their situation. The competence district level learns about is the management competence, as the decisions they make are about resource allocation [Kaspersma, 2013]. In rural Uganda the districts are considered to be organisations. However, organisations at that level are in most cases just one or two persons [Nabunnya et al., 2016]. In the case of an individual that is learning, the person would exploit its *informal-cognitive component* of the management competence by learning from the experience with a certain allocation ratio [Kaspersma, 2013]. The moment that a person at district level learns from the experience of another person we could also argue that they learn about the *cognitive-explicit component* of the management competence, as this information might be considered as an objective finding or a theory [Kaspersma, 2013].

How do the districts learn about the allocation ratio? The perspective on learning used here is the *experiential perspective*, because the districts translate experience with a certain ratio into knowledge about the relation between that ratio and the performance in their district. Second, we can observe patterns of *social learning* in this case description. Districts can learn by observing each others behaviour, relating to the behavioural perspective, and by placing the observations in their own context, thus considering a social context surrounding the subject that is learned about. The actual learning furthermore, occurs when information is extracted from those observations, enabling the districts to make a conscious decision about the observed performance.

Connected to the experiential perspective on learning is the theory about loop-learning. The loop-learning method shows cycles between actions and feedback from actions. The districts here are considered to do some basic problem-solving: the districts implement a strategy, observe the result, use the feedback and adjust their strategy. This corresponds to the single-loop learning as described by Argyris [1976], with the slight difference that districts can also observe and learn from strategies implemented by other districts. Double-loop learning considers a revision of underlying strategies and goals, this is not what the districts will try in this conceptualisation of the case.

When the actors at district level experience or *learn* allocation ratios that serve the service levels in their district best, they can share this information with other districts. In practice we can identify three ways in which districts communicate such information with each other [Nabunnya et al., 2016], the ways are also visualised in Figure 3.2:

- **Inter-district:** a representative from a DWO communicates with a representative from a DWO in another district. The two have a conversation and can share their own best practices with each other and learn best practices from the other.
- **Regional:** districts can share best practices and learn from each other at a variety of possibilities at regional level. In a District Water Officers Meeting, representatives from all districts in a region gather to share information. Regional learning alliances or regional WASH alliances are other practical fora where districts share information at regional level.
- **National:** districts can share information with each other using an indirect route via the MWE at national level. Via two ways information is transferred from district level to national level. First, there can be a direct communication line between someone in the district and someone at the ministry. Second, the official communication line is via the TSU that operate at regional level. The TSU can observe and identify successful policies in the districts and communicate this information

to the ministry. The ministry can, in turn, communicate this information back to the districts. When the information is acknowledged to be successful by the Ministry the information can be transferred by means of laws and policies that are set at national level.

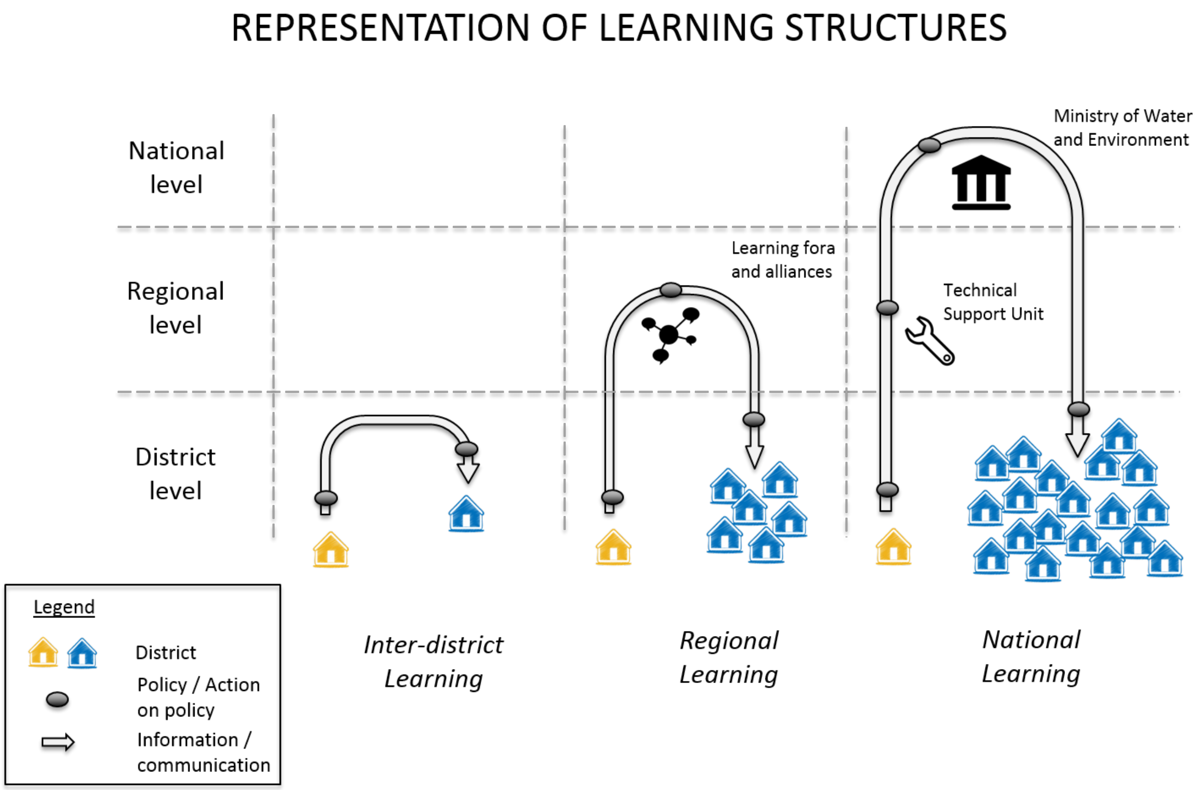


Figure 3.2. Representation of the learning structures in rural Uganda. The districts can learn from each other in three ways. The institutional levels involved in the efforts of learning are represented in the figure.

Note that the districts learn how to decide on a *single* policy in this financial case. The policy the districts learn about is the allocation ratio. In the description of inter-district, regional and national learning we have identified different structures that foster learning between districts in Uganda. The structures are static, whereas learning processes between districts are dynamic. How do districts learn how to use the allocation ratio from each other? Again, we are interested in observing how districts use a single policy, learn about the effectiveness of the policy, and transfer the effective policies between each other. For this dynamic description we use the theory of memetics. As is described in subsection 2.2.3 memetics considers a *meme* as central subject of analysis. The meme evolves through a social system, using people as its carriers. The meme can be considered as a concept or an idea. That concept or idea is transferred from one person to another. Thereby the meme is subject to three processes of evolution: selection, replication and variation. In the selection step the fitness of a meme to its environment is considered. This is comparable with rating the idea or concept: the chances that a bad idea is copied is lower that the chances for a very bright idea. Fitter memes, consequently, are replicated and thereby spread through the socio-technical system. The replication process might be subject to errors leading to all kinds of variation that is added to the meme.

In the financial case study the meme we consider is the allocation ratio that the districts decide about. A detailed description on how memetics is implemented in the conceptual model of learning in rural Uganda is provided in chapter 4. The argument to encode learning with the use of memetics is as follows: first, it can help to make the abstract concept of learning more tangible. Memetics can do this by putting the focus on the subject that districts learn about. The allocation ratio is conceptualised as were it an actual thing that moves, evolves and spreads from district to district. This makes it easier to imagine how learning occurs in an STS and it provides elements for encoding learning as we are now considering an object that is able to transfer between districts. Second, the evolutionary processes that describe how a meme evolves - selection, replication and variation - support the process of encoding learning as a clear sequence of steps is present. This sequence of steps make the coding process more easy, enlarge understanding of learning in a sector and provide handles for an extensive reflection on the use of each steps for encoding learning processes in rural Uganda with the purpose to enlarge understanding of learning in the sector. Third, the use of memetics to encode learning processes in a multi-level governance environment is relatively unexploited. By consciously implementing memetics and consciously reflecting on the methodology of implementing learning processes this research can add to understanding of the possibilities of encoding memetics into an Agent-Based Model to enlarge understanding of learning processes in a particular STS.

3.4 Rural Water as a Socio-Technical System

Sectors concerned with water supply, such as the rural water supply sector in Uganda, are characterized by their complex nature as is also depicted in chapter 2. The boundaries of a water supply system span the collection, transmission, treatment, storage and distribution of water from the source to the end-consumer [United Nations, 1997]. The sector consists of technical components, such as the infrastructure that is needed to perform all activities, and social components, such as the end-users of water and the organisations concerned with water collection and delivery. The technical and social component are closely interrelated and the sector can therefore be observed as an STS. Ongoing research on the water supply sector confirms the interrelatedness of social and technical components. The management of water resources in the last decade shifted from a focus on technical means to a focus on stakeholder involvement [Pahl-Wostl, 2007]. Furthermore, there is a demand for an integrative approach, concerning technical artefacts, humans and the environment [Pahl-Wostl, 2006]. The Global Water System Project emphasizes this statement by defining the *water system* as the following three components and their interactions: 1) human components, 2) technical components and 3) biological and biogeochemical components [Framing Committee of the Global Water Systems Project, 2005].

When we analyse the rural water supply sector as an STS we identify two separate, interrelated systems. First there is a technical system, comprised of water infrastructure. The water infrastructure delivers services to the population in the area. The infrastructure is subject to all kinds of processes that influence their state, such as maintenance, operation, weather conditions, and even the flow of water through the parts of the infrastructure. All processes influence the state of a piece of water infrastructure, e.g. heavy operation can cause a part to fail resulting in a non-functioning piece of infrastructure. Second, there is a social system that is concerned with decisions about the technical system. A network of people, organisations and governments discuss and make decisions about the infrastructure. An outcome of these processes is for instance an *action* to construct a new piece of water infrastructure or to maintain a water point that is malfunctioning. Inherent to this description of the two systems are interactions between the technical system and the social system. The social system decides on how to allocate their financial, material and personnel resources for optimal investments in water infrastructure. The water infrastructure subsequently can break down at any point in time. The breakdown of a water point is a very complex process, influenced by many variables, and therefore hard to predict [Fonseca et al., 2011]. The social system, in reaction, has to cope with this uncertainty and ideally would design structures that account for this uncertainty. A graphical representation of rural water as an STS is provided in Figure 3.3.

In the same figure a second representation is given: the financial allocation case in Uganda. There are three ways in which the case study is represented in the figure of rural water as an STS. First, the social system shows the institutional levels of interest in the case study. National, regional and district level are represented. Lower levels, as visualised in Figure 3.1, are out of the scope of this thesis, as learning processes are observed at higher institutional levels as described in section 3.3. Second, the figure shows the DWSCG budget in the form of a financial flow from national level to district level. District level uses this budget to invest in water infrastructure in the technical system. Third, a representation of the flow of information is given between the three institutional levels. This flow of information also represents the different structures of learning that were identified in section 3.3.

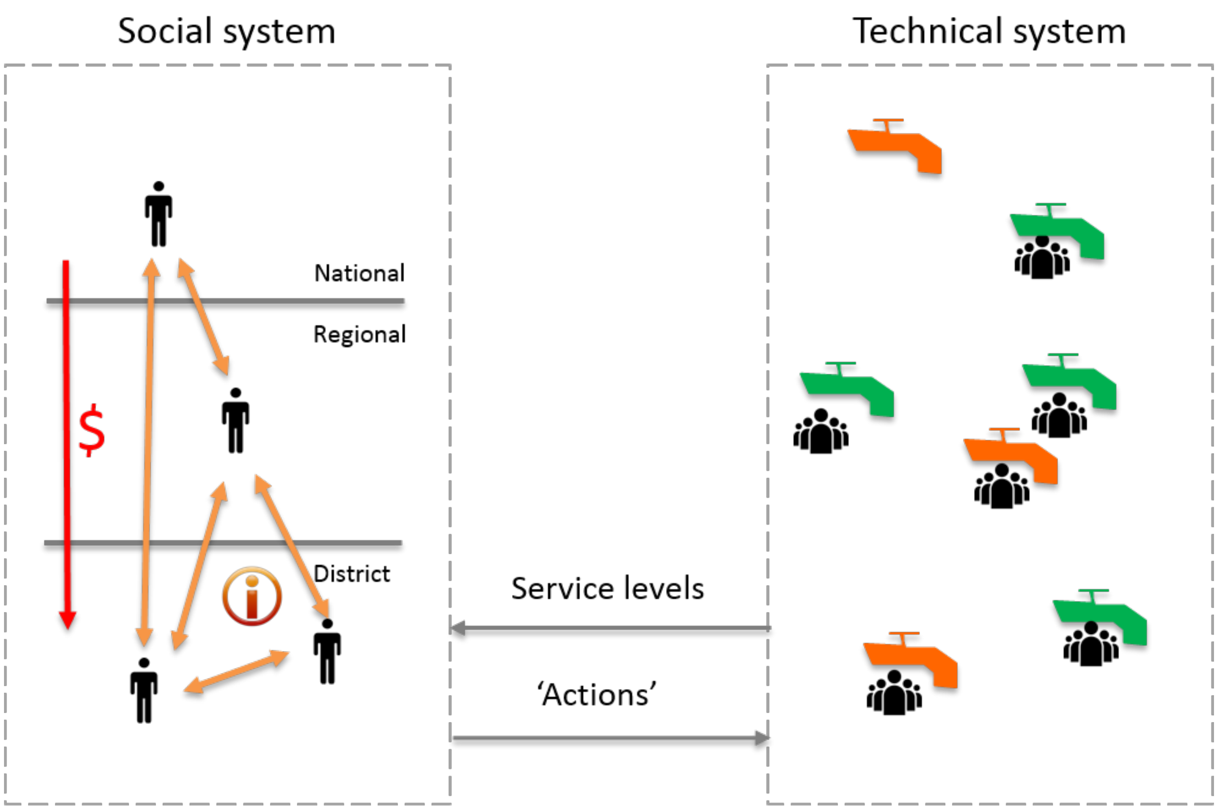


Figure 3.3. The rural water supply system presented as a socio-technical system. The case study is represented by the abstraction of institutional levels (national, regional and district), by the flow of budget (red arrow from national level to district level), and by the flow of information through the social system (orange arrows).

3.5 Rural Water as a Complex Adaptive System

A social network of actors strongly that interacts with a technical system makes the system a Complex Adaptive System (CAS). In a CAS the social network of actors defines the development, operation and management of the technical system, which in turn influences the behaviour of the actors within the social network [Dam et al., 2013]. This is also what we observe in the water supply sector in rural Uganda. Therefore, we can observe our system of interest not only as an STS, but also as a CAS. This argument serves two purposes: first, the CAS perspective has consequences for analysing the system and second, the CAS perspective provides specific modelling opportunities.

First, the CAS perspective on a water supply system has some consequences for analysing a system. A system's behaviour can be observed as a result of the cumulative action of actors in the system. Actors, or *agents*, can be any entity making decisions and thereby influencing other agents in the system or the environment. This does not mean that the balance of power in such a system is solely in the hands of the smallest decision-making entities, because they operate in a *nested* system. The actions of agents are bound by all kinds of mechanisms in a system, such as rules, laws and culture. Despite the nestedness of a system a CAS often shows non-linear behaviour. Non-linearity refers to the non-trivial transition from an input to an output through the system [Dam et al., 2013]. Through a course of interactions between agents, acting based on the decisions of other agents or acting based on internal information, the output of the system with a certain set of inputs is hard to predict. An implication for a water supply sector is for instance the difficulty to predict the outcomes of envisioned policies as a result of the variety of reactions of individual agents to the proposed policy and the cumulative effect of the individual reactions on the output of the system.

The complexity of a water supply system is enlarged by the presence of multiple institutional levels. This spans from government level to local level and all possible levels of governance in between. The most important take-away from CAS is that the behaviour of the system cannot be fully controlled by a top-down approach, but the system's behaviour emerges out of the interactions of agents in the system.

Observing the rural water supply sector in Uganda as a CAS has, as we have seen, consequences for analysing the system. In this research I am exploring the effects of learning on the water service levels in the sector. In chapter 2 I have described different ways to perceive learning. In this chapter we have seen in section 3.3 that there are three different routes that a district can use to disperse and take up information. We now need a method to explore different perceptions of learning in theory and different routes of information spread in the rural sector. A relatively *cheap* method is provided by modelling, where experiments can be conducted *in silicio* [Dam et al., 2013].

A method that performs well on modelling and simulating CAS is Agent Based Modelling. In an ABM agents are created that behave according to a set of decision rules. An agent can be an abstraction of a person or an organisation or any other entity observed in a real system. Agents can act and interact in an environment, providing the opportunities to explore aggregated system behaviour that emerges from a series of agent actions and interactions. In chapter 4 is described how such a model can describe learning in the Ugandan rural water supply sector. The actual implementation of the agents is subject in chapter 5.

4 | Conceptualisation of Agent Based Model

In this chapter learning in the Ugandan rural water supply sector is conceptualised to enable encoding in the Agent Based Model. Previously, in chapter 3 the rural water supply system in Uganda is described. First by describing the multi-level governance environment in rural Uganda in section 3.1 and second in the financial case study in section 3.2. In chapter 2 we have seen how learning in a Socio-Technical System can occur and in section 3.3 the decomposition of learning is applied to the financial allocation case in the Ugandan rural water supply system. In this chapter these two - learning and rural Uganda - are combined in a conceptualisation of an ABM. The ABM is used to observe the influence of learning on water service levels in the Ugandan rural water supply system. In section 4.1 the conceptualisation of the rural water supply sector is described. Throughout the section the key assumptions are gathered. We do this because the conclusions about the model outcomes need to be observed in the light of the assumptions. The assumptions are summarised in Table 4.2 and Figure 4.1 shows where the assumptions engage with the financial case study visualised as an STS. Next, in section 4.2 the conceptualisation of learning in the rural water supply sector. In this part I describe how the agents in the concept of the sector are able to learn and what rules they follow to spread policies to other agents. The assumptions made in this section are summarised in Table 4.5.

4.1 Conceptualisation of Water Supply System in Agent Based Model

In this part the conceptualisation of the water supply system related to the financial allocation case is described. Three institutional levels are identified in the social part of the system: national level, regional level and district level. Within these levels learning processes, described in section 4.2, lead to decisions about water infrastructure. District level receives a District Conditional Grant (DCG) from national level and invests this budget in the water infrastructure in the district. The assumptions that are made for the subsequent parts are described below.

Representation of Institutional Levels The national government provides financial support to the districts. The financial support is meant to help the districts to achieve adequate water service levels for the district population. Financial support is provided by means of the DCG. Every year, national

Government calculates the DCG budget for every district. There is no limit on the cumulative budget available for the grant. For the sake of the ABM we assume that national level has an infinite budget for the financial support of the districts. The DCG budget calculation is based on the formula set at national level [Ministry of Water and Environment, 2013a].

Assumption 1: National government has infinite budget.

The national government is an important stakeholder for the spread of policies through the system. National government can spread a policy through the system by making the policy mandatory for all other districts in Uganda. An allocation ratio that proves to result in high water service levels in one district, can be transferred to all other districts by national level.

Regional level in the system is geographically represented by the region covered by a Technical Support Unit (TSU) in Uganda. A TSU covers a region consisting of multiple districts. The number of districts in a TSU vary from 8 districts to 24 districts. There are 8 TSUs in Uganda. At the regional level learning processes of districts are supported. District Local Governments (DLG) gather at regional level to share best practices and learn from each other. At regional level there are District Water Officers Meetings, learning fora and WASH alliances, representing different venues where districts come together to share the water service levels in their district and a selection of their policies.

District level is represented by the DLG. The DLG is the lead authority in the district concerned with the delivery of water services to the district population. The DLG receives financial support from national Government by means of the DCG. The DCG is spent on water infrastructure in the district. Investments in water infrastructure are done in a variety of ways. Different categories of expenditures are represented in Table 3.1. The districts may not have spent all available budget in the financial year. This residual budget cannot be used by the district in the following year. The leftover budget is returned to national level.

Assumption 2: Residual budget at district level is returned to national level every year.

The representation of the districts in the ABM is based on the actual districts in Uganda. The districts are similar in terms of population, water service level, TSU region, functionality percentage of water infrastructure and they carry the name of their real counterpart. Geographical details of the district, however, are not represented in the model. This has consequences, such as the exclusions of suitability of different types of water infrastructure caused by the available water resources per district and the exclusion of the distance people have to cover to reach the nearest water source.

Assumption 3: Districts are all the same in terms of possibilities created by geographical characteristics.

An important abstraction is the absence of geographical complexity as previously mentioned in *assumption 3*. In the conceptualisation of water points in a district the location of the water points are not considered. This is reflected in the variable used for measurement of the water service level in a district and in the type of water infrastructure. Different geographical characteristics make different types of water infrastructure more suitable than others. This geographical complexity is not considered in the model. This information adds little to answering the research questions, but has a big influence on applicability of the current methodology and modelling techniques. The implications for the variable measuring water service level is described in section 4.2.

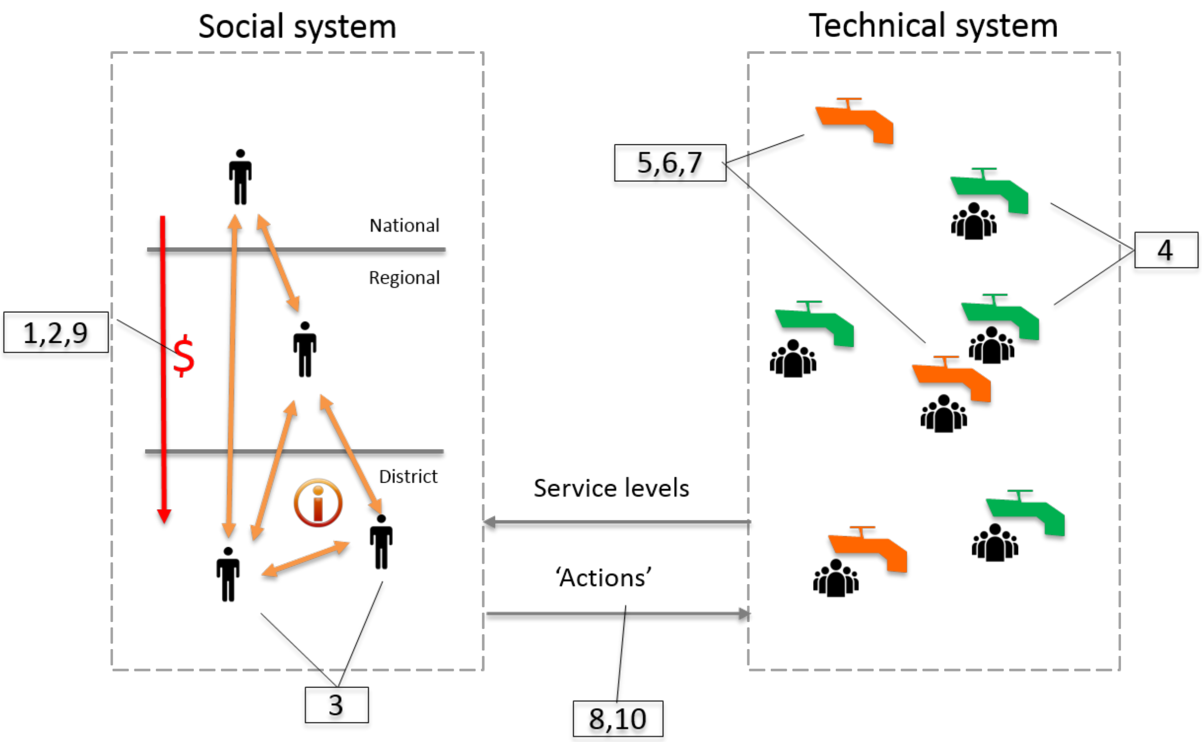


Figure 4.1. Overview of the assumptions that are made in the conceptualisation of the system. The point where the assumptions engage with the STS is shown by the numbers. The numbers correspond to the number of the assumptions in this section.

Representation of Water Infrastructure In Uganda there is a variety of types of water points present in a district, for instance shallow wells, dams, valley tanks, rainwater harvesting tanks, boreholes, kiosk taps and piped schemes. In the conceptualisation only one type of water infrastructure is considered. The conceptualisation considers water points of the type shallow well with a hand pump constructed on top of the well. The total amount of water that these water points together deliver corresponds to the cumulative quantity of water delivered in the district by the cumulative of other water points. The cumulative quantity of water delivered in a region by the variety of types of water points is calculated, based on data gathered in Uganda district [Ministry of Water and Environment, 2015, Directorate of Water Development and Ministry of Water and Environment, 2016].

Assumption 4: All water points in the ABM are shallow wells operated by a hand pump.

This assumption has implications, as different types of water points have different characteristics and behaviours, for instance for the construction price, expected lifetime, the costs of major maintenance on the water point or causes for breakdown of the infrastructure. However, the complexity that arises from the variety of water points is not the focus of this research. This research is focussed on how policies are spread trough the rural water system. A representation of the water system with one type of water point and a representable number of those water points is considered sufficient for this research. It is a caveat though.

The breakdown of water infrastructure is the result of many different variables and is hard to predict [Fonseca et al., 2011]. The breakdown is for instance dependent on the (minor) maintenance the water point receives, the way the community operates the infrastructure, geographical characteristics of the location and the quality of materials and installation. Causes for breakdown of water infrastructure are found in both the social system and the technical system. Social dynamics influencing the breakdown of water infrastructure are examined in other recent research in rural Uganda [Nava Guerrero, 2016].

In this conceptualisation of the system the complexity of water point breakdown is peered down to a probability distribution. As the research is focussed on the spread of policies through the system, the water points and the way a water point breaks down are subordinate to the dissemination of information. To focus on the spread of information, the water points are assigned an expected lifetime drawn from a normal distribution. The moment the age of the water point reaches the expected lifetime, a water point is assumed to break down and becomes non-functional. The probability distribution chosen is a normal distribution with mean 6 and standard deviation 1.5. This distribution gives a good representation of water point failure, as water points in practice accidentally fail within a year or can occasionally reach a lifetime of 12 years [Moriarty, 2016]. The breakdown of a water point, a shallow well operated by a hand pump, is considered as the complete breakdown of the installed hand pump. In major maintenance performed on a non-functional water point the hand pump is assumed to be taken of completely and be replaced by a new hand pump. The water points age and break down. If a water point is non-functional for 5 years, the water point is considered abandoned [Directorate of Water Development and Ministry of Water and Environment, 2016].

Assumption 5: Failure of a water point is normally distributed with a mean of 6 years and a standard deviation of 1.5.

Assumption 6: A major maintenance operation of a water point entails the complete replacement of the hand pump.

Assumption 7: A water point that is non-functional for a period of 5 years is considered abandoned.

Representation of District Conditional Grant The DCG in Uganda is composed of five different types of expenditures as shown in section 3.2. National level dictates the boundaries of the ratio a district can use to spend the budget. The conceptualisation of the water infrastructure and the focus on rural water provision demands an adjustment to the conceptualisation of the ratio. In the conceptualisation the ratio consists of three different factors: X, Y and Z. National government still dictates the size of the ratio. An explanation of the factors is given below, an overview is presented in Table 4.1:

X represents the budget reserved for Capital Expenditure (CapEx). CapEx is used to construct a new water point. Installation of a new water point includes the construction of a shallow well and the placement of a hand pump. National level dictates that at least 70% of the DCG is to be spent on CapEx.

Y represents the budget reserved for Capital Maintenance Expenditure (CapManEx). CapManEx is used for major repairs of water points. A major repair represents the complete replacement of a hand pump. Similar to the conditions in the DCG at the most 13% of the budget in the grant may be spent on CapManEx.

Z is the fraction of the budget not spent within the financial year. It is assumed to be returned to national government. The budget is not spent on CapEx or CapManEx. Unspent budget can represent a number of things in practice:

- The system can get clogged, causing a variety of delays, such as bureaucratic delays, a lack of planning skills or a lack of work force to get the projects started.
- Unspent budget caused by a lack of integrity.
- Efforts to monitor the status of water infrastructure in the district are too low. Information about WP that need repair lacks. The budget isn't spent, because the district water office doesn't know repairs are needed.
- It represents allocation conditions in the DCG that are not considered in the model, for instance, the budget for investments in sanitation.

	Definition	Short	Boundaries (% of DCG)
X	Capital Expenditure	CapEx	70 - 100
Y	Capital Maintenance Expenditure	CapManEx	0 - 13
Z	Unspent Budget	Unspent	0 - 30 (100 - X - Y)

Table 4.1. Conceptualisation of the District Conditional Grant

Assumption 8: The allocation ratio is composed of three factors: X (ratio of CapEx), Y (ratio of CapManEx) and Z (ratio unspent budget).

In Uganda the amount of budget that the districts receive is based on an allocation formula [Ministry of Water and Environment, 2013a]. In section 3.2 we have seen how the formula is designed to serve the unserved communities and that the formula provides a disincentive for the districts that reached water service levels that are above average. In an attempt to implement the formula to calculate the budget that districts would receive a total of 31 districts would receive a negative budget in the initial conditions. Addition of the second condition in the ratio, stating that a district always receives a budget for minimum investments, gets rid off the negative budgets. However, since no definition for *budget for minimum investments* is presented in the formula, the budget that the districts with a negative budget would receive is unclear. Therefore I choose to use the budget the districts actually received in the past year (FY 15/16), retrieved from Ministry of Finance Planning and Economic Development [2016]. Next, I assumed that this budget represents a budget that is representable for the relative water service level compared to the national average service level. The budget in the formula grows with same rate as the population growth and can grow or decline with the service levels that are reached in the district and in the nation. As calculation of the water service levels would cause similar troubles as in the starting condition, I assume that the budget in the DCG only grows with the growth of the population.

Assumption 9: The budget allocated to districts is based on the actual budget in Financial Year 2015/2016 and grows with the same rate as the population growth.

District Investment Strategy The DCG and the allocation ratio jointly form budgets for CapEx and for CapManEx. Districts spend their budget accordingly. The districts are assumed to invest the full available budget on both expenditures, independent of the service level and the current state of infrastructure in the district.

Assumption 10: Districts spend all budget without considering the status of the infrastructure in their district.

Districts invest in new infrastructure first. Residual budget from CapEx, money that is within the CapEx budget and is less than the price of the installation of one water point, is assumed to be transferred to CapManEx budget. The choice to invest in new infrastructure first, is made because it is far more attractive for policy makers to invest in new infrastructure than to repair non-functional – old – infrastructure, because it makes a government look much better. The argument for infrastructural investments is not in efficiency of resource allocation, it is about political power and posturing [Nabunnya et al., 2016].

#	Content of the Assumption
1	National government has infinite budget
2	Residual budget at district level is returned to national level every year
3	Districts are all the same in terms of possibilities created by geographical characteristics
4	All water points in the ABM are shallow wells operated by a hand pump
5	Failure of a water point is normally distributed with a mean of 6 years and a standard deviation of 1.5
6	A major maintenance operation of a water point entails the complete replacement of the hand pump
7	A water point that is non-functional for a period of 5 years is considered abandoned
8	The allocation ratio is composed of three factors: X (ratio of CapEx), Y (ratio of CapManEx) and Z (ratio unspent budget)
9	The budget allocated to districts is based on the actual budget in Financial Year 2015/2016 and grows with the same rate as the population growth
10	Districts spend all budget without considering the status of the infrastructure in their district

Table 4.2. Overview of Assumptions in System Conceptualisation Phase

4.2 Conceptualisation of Learning in Agent Based Model

This part describes how learning is conceptualised in the ABM. Learning in the ABM is understood as the transfer of policies from one district to another. Previously, in section 2.2, we have seen how the theory of *memetics* can describe how a piece of information evolves as it is transferred from person to person. In section 3.3 the argument for memetics as a method to encode learning is given and we have seen how memetics is applied to the rural water supply system in Uganda. This section describes how memetics is used to describe how policies are transferred between districts in the ABM.

The policy under attention is the allocation ratio. There are two degrees of freedom in the decision about the allocation ratio: X, the ratio for CapEx, and Y, the ratio for CapManEx. Z, the ratio for unspent budget, is the result of choices made for X and Y (see also Table 4.1). Following the theory of memetics the allocation ratio becomes the subject of analysis, i.e. the *meme*. To understand the process of cultural evolution that is described by memetics, we must consider the meme in terms of *fitness* with its environment [Heylighen and Chielens, 2009]. A meme that is sufficiently adapted to its Socio-Technical environment is more likely to be propagated than one that is not. The process of *selection* determines how fit memes are to their environment.

4.2.1 The Selection Process

By the process of selection the fitness of an allocation ratio, the *meme*, to its environment is determined. This means we must determine how to measure the fitness of an allocation ratio in the rural water supply system and therefore we turn to how progress is measured in the sector itself. Progress in the Ugandan water sector is measured in water service levels. In Uganda four different indicators for water service levels are used: water quality, water quantity, water reliability and water accessibility. The indicators and national standards are shown in Table 4.3.

Indicator	**Metric - National Standard (Goal)**
	Water Quality
E. Coli	Not detected in min. 95% of samples. Not detected in max. 4% of samples
	Count 1 in max. 1% of samples of 100mL
Total Dissolved Solids	500 mg/L
Turbidity	5 Nephelometric Turbidity Units
	Water Quantity
Quantity Delivered	>= 20 litres per person-day
Quantity Accessed	No national standard specified
	Accessibility
Number of Users	Borehole: 300 persons, 60 households
	Shallow well or spring: 200 persons, 40 households
Distance to Facility	% of people within 1 km of WP
Walking Time	No national standard specified
	Reliability
Uptime of the Source	No national standard specified

Table 4.3. Water Service Levels in Uganda: indicators and goals. Adapted from Nava Guerrero [2016], based on Biteete et al. [2013].

Now we consider a situation where an allocation ratio results in relatively high water service levels in a district. This allocation ratio is considered a *good* or *effective* ratio. Consequently, a ratio is considered *poor* or *ineffective* when it results in relatively low water service levels in a district. Note here that water service levels are used as an indicator of performance for the allocation ratio. The effect of the allocation ratio on water service levels in a district is not direct, as water service levels in a district depend on more variables than only the allocation ratio. In the financial case study it is the most direct tool that districts have to alter their water service levels.

However, in the current conceptualisation of the rural water supply system not all of these indicators can be measured with the same ease. In this paragraph I describe how the water service level is conceptualised in the ABM. This parameter is also used to determine the fitness of an allocation ratio to its environment, thereby changing the survival chance of a ratio as is described further on in this subsection. The water service level that is used in the ABM is a representation of *Water Quantity*. I name it a representation, because there are more service levels included in the performance indicator as is described in Table 4.3. Water Quantity is measured in litres of water per person per day. This calculation is based on an assumption about the delivery capacity of water infrastructure that is used in Uganda. In our case, a shallow well is assumed to deliver 20 litres of water for 300 persons every day [Directorate of Water Development and Ministry of Water and Environment, 2016, Ministry of Water and Environment, 2015]. In the ABM the total amount of litres delivered is divided by the total population, resulting in a service level: water quantity measured in litres of water per person per day. This has two important impacts: first, crowding in the accessibility indicator (Table 4.3) is represented in the model. Second, water service levels are aggregated at the district level. This has implications for comparison with the coverage indicator that is often used by the Ugandan government to rate the rural water supply system [Ministry of Water and Environment, 2015, Nimanya et al., 2011]. Furthermore, a source that is non-functional in the ABM delivers 0 litres of water, this means that the reliability indicator is present in the water service level that we use in the ABM.

That leaves two indicators absent in the ABM. First there is the indicator for water quality. Water quality is dependent on too many variables that are not present in the study, therefore I decide to leave water quality out of the scope of the research. Second, as we have seen in the previous section, the districts in the ABM are all assumed to have similar geographical characteristics. There is no geographical representation of water infrastructure considered in the ABM. This has implications for the representation of the accessibility indicator, as we cannot specify neither the distance to a water point, nor the walking time.

Lastly about the measurement of performance - hereafter I elaborate on the considerations about the fitness of a ratio and corresponding implications - I assume that the districts have full information about the state of their infrastructure. I assume this, because the full information is needed to rank and rate the performance of a district. In Uganda full information is often not the case as is, at the least delayed. In the ABM the information is considered to be available right away.

Assumption 11: The water service level in a district is measured in litres of water per person per day, aggregated at district level.

Assumption 12: District have full information about the state of the infrastructure.

The performance of an allocation ratio is measured in the water service level of the district that applied this ratio. It is easy to imagine that higher water service levels are considered better than lower water service levels. However, the selection step considers what ratios are fit in their environment and what ratios aren't, in other words: what ratios are replicated and live on and what ratios are not replicated and grow extinct. Therefore, we still need an indicator of a *good* and a *bad* allocation ratio. This is done in two ways. First, we *rank* the districts according to performance measured in water service levels. Ranking means that we make a list of the districts based on the water service level - water quantity - they deliver in their district. Districts are ranked highest to lowest water service levels. This represents two mechanisms that we can observe in practice. First, districts observe and ask how other districts are performing. If a difference of 20%-30% in performance occurs, a district tries to imitate the policies or structures used by the other district [Slinger, 2016]. Second, the ranking provides an efficient method to stimulate performance. Evidence from the South-African water system shows that when a ranking is made public the bottom 50% of the ranking is pressured to actively seek for solutions [Department of Water and Sanitation, Republic of South Africa, 2016]. We use this ranking from the South-African system to determine what a good water service level and thereby a good allocation ratio is: the ratio of districts that perform in the bottom half of the ranking is considered bad, the ratio of a district performing in the top half is considered good.

For the second method to determine whether a ratio performs good or bad the national goals and standards on water service levels are used as indicator. In Uganda a simple algorithm is used to determine how good a water service level is. An overview of indicators of the performance of a water service level in Uganda is provided in Table 4.4.

Water service level	Scenario
Excellent	Good quality water supply of at least 40 litres per person per day (lppd) within a distance of 0.5 km from a water source that is reliable 95% of the time
Good	Good quality water supply of at least 30 lppd within a distance of 0.75 km from a water source that is reliable 95% of the time
Fair	Good quality water supply of at least 20 lppd within a distance of 1 km from a water source that is reliable 95% of the time
Low	User access a service that doesn't meet one or more of the following standards: quality, quantity, and reliability
Very Low	Community doesn't have an improved water source within a walking distance of 1 km

Table 4.4. Indication of performance of water service levels. Based on Biteete et al. [2013]

In the ABM a water service level that is *fair*, i.e. 20 litres of water per person per day, is considered to serve as the *target quantity*. The target quantity functions as a threshold value. Any district that scores below this target quantity in Uganda is considered to have an *insufficient* water service level.

The ranking and the threshold quantity combined lead to the following consideration of a *good* allocation ratio: an allocation ratio that leads to a water service level in the district that is above the target quantity of 20 litres of water per person per day **and** is ranked in the top half of the district ranking. Consequently an allocation ratio that result in a districts water service level below the target quantity **or** in the bottom half of the ranking is considered *poor*. A visualisation of an example selection process is provided in Figure 4.2.

Assumption 13: Allocation ratios are selected based on a ranking and on the nationally set target water quantity.

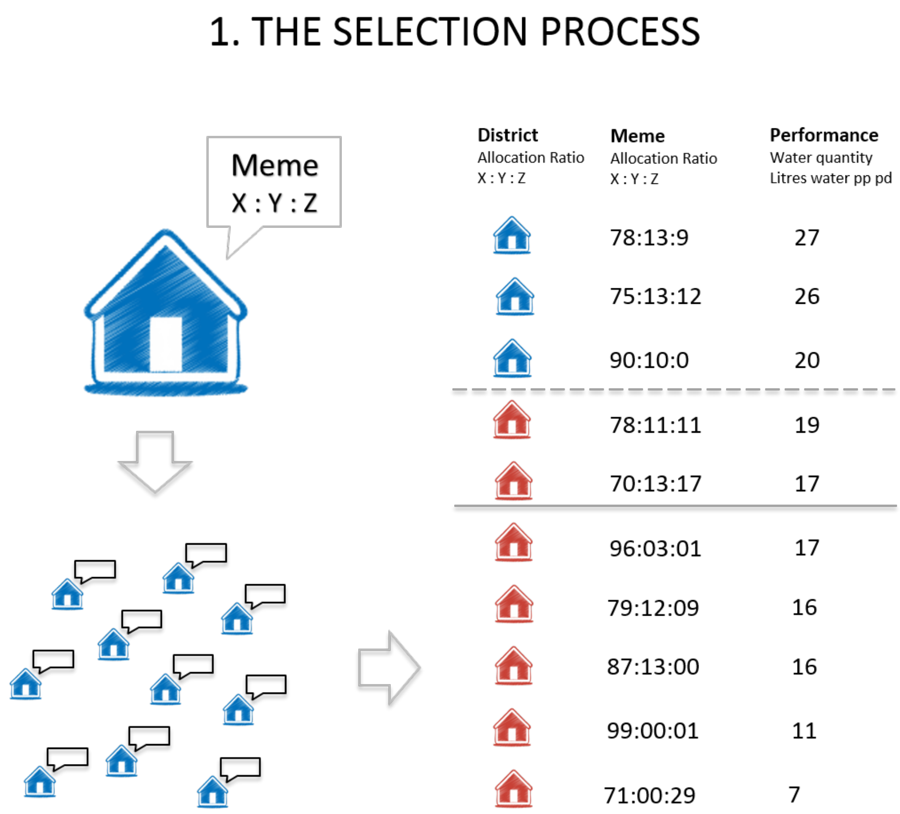


Figure 4.2. In the top left a blue house is drawn representing a district. The district carries a meme: the allocation ratio. The performance of the districts in the system is measured in water quantity. The selection procedure is shown in the right. First by the ranking that is made. Ratios that made the district perform in the bottom half are considered bad, represented by the red colouring of the district. The straight line in the ranking shows the bottom half. The dashed line shows the second selection mechanism, a threshold or target quantity of 20 litres of water per person per day.

4.2.2 The Replication Process

In the replication step is decided what allocation ratio is replicated and which districts replicate a ratio. In the selection step good and bad ratios are distinguished. This distinction is the basis of the replication step: good allocation ratio can be propagated, i.e. they can be spread to other districts. Bad allocation ratios are not propagated. This means the district with a bad allocation ratio is assigned a new ratio. The ratio they choose is determined by the best performing district within sight. What I mean with *within sight* is described further on in this subsection. All districts that perform well use the same allocation ratio in the next time step. This represents the idea that the meme lives on.

> **Assumption 14:** Allocation ratios that are considered bad are not replicated, i.e. they *cease to exist*. Good allocation ratios are replicated, i.e. they *live on*.

Districts that used an allocation ratio that is considered bad, replicate an allocation ratio from another district in the next time step. They are assumed to replicate the allocation of the best performing district *within sight*. The sight of the districts is based on the governance levels in Uganda (section 3.1) and the different ways in which districts communicate with each other - the learning structures: inter-district, regional and national (section 3.3). These three scales of communication are applied by three conditions in the ABM. The national learning structure corresponds with the fully rational replication method, the regional learning structure with the myopic replication method and the inter-district structure with the random replication method. The method and what they represent is described below.

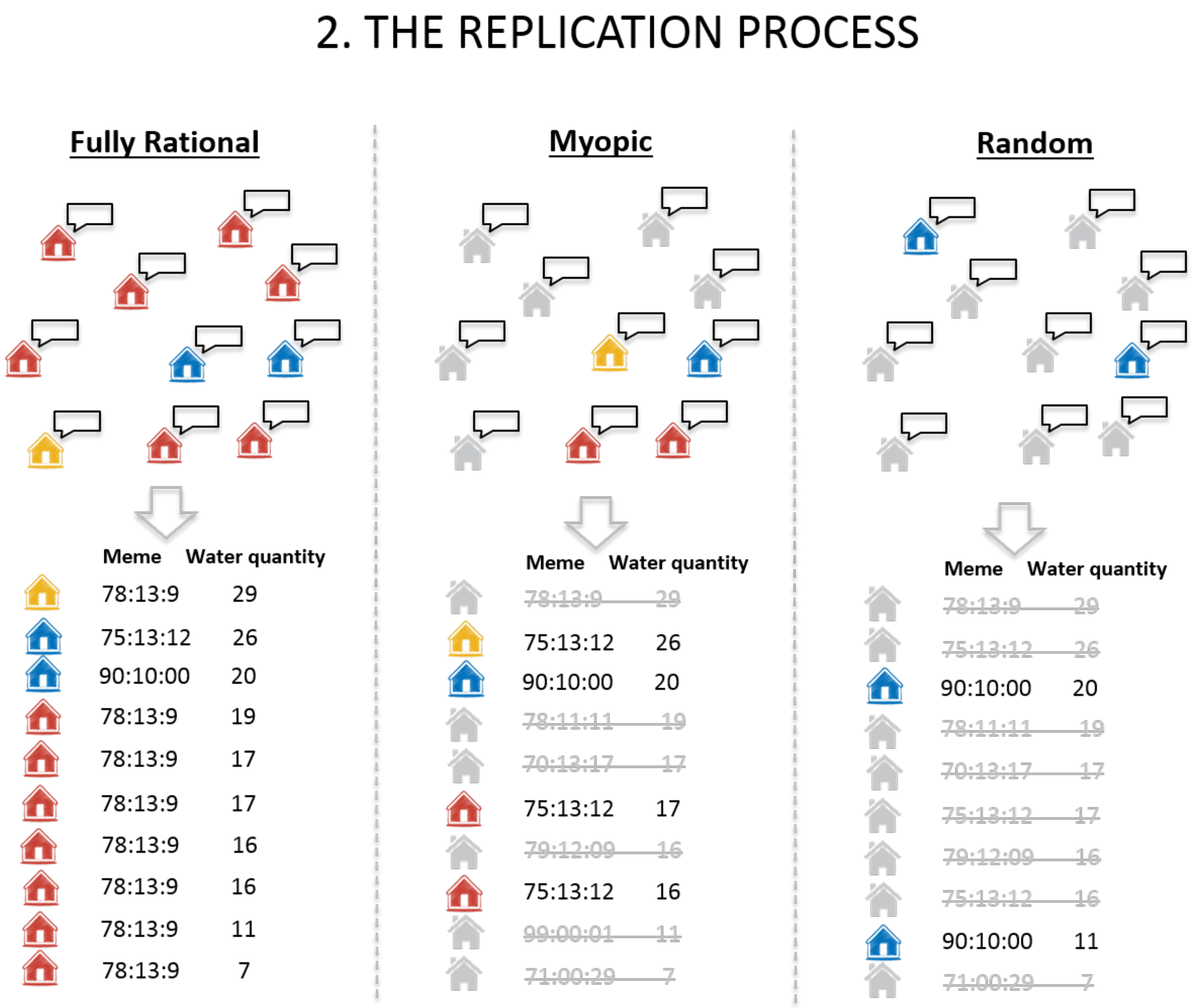


Figure 4.3. Three methods for replication. In the **fully rational** method the ratio of the best performing district (the yellow one) is spread to all districts that perform *bad*. In the **myopic** method the district can only see the performance of the districts in their region. The ranking is remade at this level and the ratio of the best performing (again yellow) district is spread to those below target quantity or in the bottom half. In the **random** method every district chooses a random other district and replicates this ratio. No ranking is made here and districts are assumed to know only their own performance.

Fully rational: a district has full information about all districts. The district replicates the ratio from the district at the top of the national ranking. This represents a situation where information is known and shared nationally. In the rural water supply sector in Uganda this represents the cycle where a district learns an effective policy and this is recognised by the TSU at regional level. The TSU at regional level monitors progress and, if the policy indeed turns out to be effective, shares this knowledge with national level. National level in turn can make the policy mandatory for all other districts.

Myopic: a districts has limited information, it only has information about the districts in its own region. The district selects the ratio of the top ranked district in the region. This situation represents regional exchange between districts. At regional level district come together at a variety of venues, e.g. learning fora, WASH alliances and District Water Officer Meetings, to share best practices with each other.

Random: a district only communicates with one other district that is randomly selected. This district does not have to be a neighbour. The random option represents inter-district communication, where representatives of two districts (accidentally) speak to each other.

The method of replication represents the ways in which districts in the rural water supply system in Uganda are able to learn from each other. A visualisation of the process is shown in Figure 4.3. The previous leads to the following assumption:

Assumption 15: Districts replicate another ratio when they are performing poor. The ratio they replicate is the ratio of the top ranked district under the conditions of fully rational, myopic or random.

4.2.3 The Variation Process

At this point, districts have chosen an allocation ratio to replicate. In the variation step the ratios are varied. To avoid misunderstanding: districts that replicated their own ratio do not variate their ratio. The variation step provides two possibilities once a ratio is selected: make a perfect copy of the ratio or slightly adjust that ratio. In case of the second condition, the districts *move* from the ratio they used in the previous year to the ratio they are assigned to use in the next year.

Assumption 16: When districts replicate an allocation ratio from another districts, they vary the selected ratio by making either a perfect copy, or adjust the ratio with a fraction between the selected ratio and the ratio used in the previous year.

The variation step in this research can represent two different processes: an unconscious variation of the policy and a conscious action to change the policy. The unconscious variation is very similar to the variation process in genetics. Species reproduce themselves by making perfect copies of themselves. The process of copying, however, is not flawless and occasionally mistakes are made. This process is most determining in evolution. These *mistakes* can turn out good, e.g. the development of an eye that enhances survival chances of a species, but most of the times the mistakes are not beneficial to the offspring. However, if this process is repeated on a massive scale, over an enormous time span, we can understand how species gradually evolve to a variant that is more fit to the environment.

The process of unconsciously adding variation to the allocation ratio in the field of memetics can be understood as an error in communication. Imagine for instance an interpretation error of the receiving district, an communication error between the districts such as a non-intentional communication of an old allocation ratio. In the ABM this step is implemented as a random step from the old allocation ratio of the receiving district towards the selected allocation ratio.

The variation step can also represent a conscious decision to alter the ratio. The districts make a choice to vary the allocation ratio that they receive. This choice represents the conscious decision to adjust the selected allocation ratio to their own situation. Success of an allocation ratio in the one district is no guarantee for success in another. This is fed by the characteristics of a district. The district can therefore adjust the allocation ratio that they receive to the situation of their own district.

The implementation of the variation step for the conscious decision is included by adding a one-year memory to the districts. The districts remember what ratio they used in the previous year, subsequently they select an allocation ratio for the next year and finally they move a fraction from the ratio from their memory to the selected ratio.

Concluding, variation of a ratio that is replicated from another district can represent two things in practice: firstly, a communication or interpretation error. Second, the assumption that a district adapts the policy from another district to their own situation before implementing it. The conscious interpretation of variation is implemented by a one-year memory and the unconscious variation is added by the addition of randomness to the movement toward the other ratio. This leads to the following two scenarios in the variation step, also represented in Figure 4.4:

1. **Perfect copy:** a district blankly imitates the ratio it has selected.

2. **Random fractional:** a district moves a random fraction from the ratio that the district used in the previous year to the selected ratio.

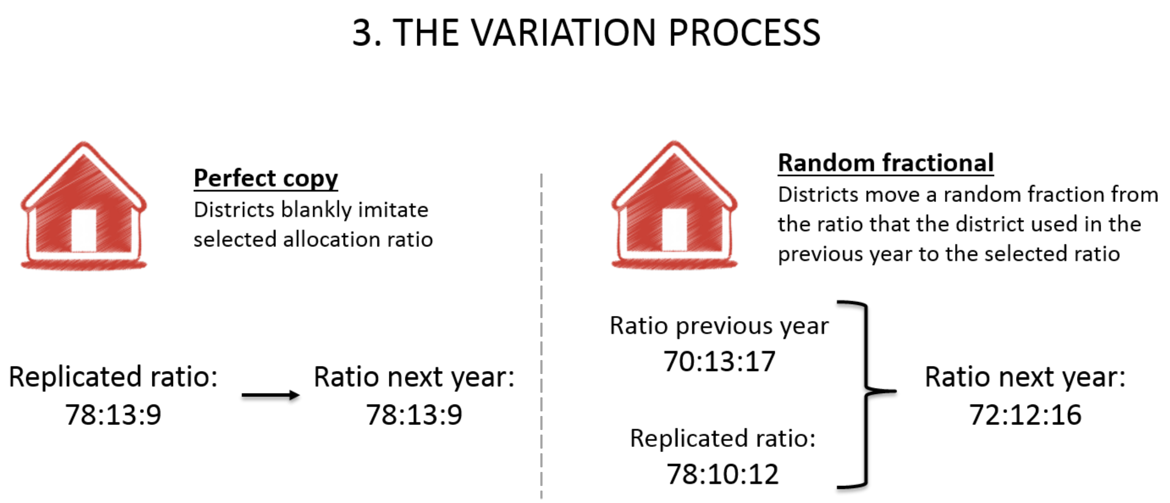


Figure 4.4. The district either make a perfect copy or they move a random fraction. The random fractional step represents both the conscious decision to add variation to the ratio and the unconscious process.

In this section we have seen a conceptualisation of learning in the Ugandan rural water supply system. Districts can learn from each other what allocation ratio they should use to reach a higher performance than their own. In the process of learning the allocation ratio is the subject. The ratio evolves through the system, following the processes of selection, replication and variation. An overview of the assumptions in this part is provided in Table 4.5.

Assumption Number	**Content of the Assumption**
11	The water service level in a district is measured in litres of water per person per day, aggregated at district level
12	District have full information about the state of the infrastructure
13	Allocation ratios are selected based on a ranking and on the nationally set target water quantity
14	Allocation ratios that are considered bad are not replicated, i.e. they *cease to exist*. Good allocation ratios are replicated, i.e. they *live on*
15	Districts replicate another ratio when they are performing poor. The ratio they replicate is the ratio of the top ranked district under the conditions of fully rational, myopic or random
16	When districts replicate an allocation ratio from another districts, they vary the selected ratio by making either a perfect copy, or adjust the ratio with a random fraction between the selected ratio and the ratio used in the previous year

Table 4.5. Overview of Assumptions in Learning Conceptualisation Phase

5 | Model Specification and Verification

In this chapter the implementation of learning in rural Uganda in the ABM is described. In chapter 4 the conceptualisation of the rural water supply system was described as well as the conceptualisation of learning in the sector. This conceptualisation alone is not enough to construct an ABM that enables to analyse effects of learning in the sector. In section 5.1 I describe what different types of agents are present in the ABM and how they are conceptualised. The section defines what the agents are, what properties the agents have and how they interact in the ABM. In section 5.2 we go into the parametrisation of the model environment. Here we see for instance the considerations about time in the ABM and some of the core procedures in the ABM. This section also elaborates on some core formulas that implement the processes of selection and variation. Finally, the ABM is constructed and in section 5.3 the working of the model is showed and I verify whether *the model is built right* [Dam et al., 2013]. In the so-called verification of the model I prove that my implementation of the conceptual model of learning in rural Uganda in the ABM is correct. First some core concepts concerning an ABM are explained.

An ABM is a computational model for simulating actions and interactions between autonomous agents. There are a few important concepts in an ABM that are important to understand at this point: the agent, the environment and time. An **agent** is the smallest element of an ABM [Dam et al., 2013]. Agents are autonomous, because they act based on states and rules. Agents are able to perform actions that influence themselves, other agents or the environment. Vice versa, agents also receive inputs from actions and states of other agents. Key takeaway about agents is that they are a very important part of the model: agents act and interact with each other, based on a set of states and rules that the modeller assigns to them.

The agents act and interact within an **environment**. The environment is everything that is in the ABM, but is not an agent [Dam et al., 2013]. The agents *live* in the environment and therefore the environment is often used to structure the actions and interactions of agent. In the case study of this thesis the environment can contain for instance the rules of national government that structure districts behaviour. Next to structure, the environment contains all sort of information that the agents use in their decision making processes. The environment is not a passive thing, it can be actively interacting with the agents and it can be dynamic, for instance as a result of certain agent-environment interactions.

Third, the notion of **time** is important in an ABM. Since we are dealing with a computational model, we have to deal with discrete time. The time step that is considered in an ABM is called a *tick*. In a tick agents act and interact according to their specified set of rules. A tick can represent any entity of time:

a second, a week, a decade. A heuristic that can be followed for the length of a tick is that is should represent the smallest time step of interest in your system. Furthermore, we assume parallelism of time in an ABM [Dam et al., 2013]. This means that we assume all actions within a tick are performed in parallel, whereas in the ABM they are actually performed one by one. In the ABM, if multiple agents perform an action, the order of these actions is chosen randomly by the software [Wilensky, 2016]. This is important to consider, because actions that are dependent on each other can result in different outcomes based on the order they are performed in. Another consideration that is time related is the total simulation time. A heuristic that is often used is that the simulation time is similar to the largest time scale of interest.

5.1 Agent Parametrisation

In the ABM there are three types of autonomous agents: TSUs (Technical Support Units), Districts and WPs (Water Points). With these agents the dynamics of the systems of interest, learning in rural Uganda, can be represented. The TSU-agent represents the regional level in Uganda, the District-agent represents the districts, and the WP-agent is used to represent all water infrastructure in the system. Given the conceptualisation in chapter 4 we now only miss a representation of the national level. The national level is represented in the *environment* of the ABM and is described in the next section, section 5.2. This section describes how the agents are parametrised. This includes what properties the agents posses, what states they consider and what interactions they have with other agents or the environment.

5.1.1 TSU-agent: Regional Level

The regional level is represented by the TSU-agent. The TSU-agent firstly represents a geographical demarcation in Uganda. Multiple districts in Uganda belong under the supervision of a certain TSU. The number of districts in a TSU region varies from 8 to 20 districts. In total there are 8 TSUs in Uganda and therefore also 8 TSU-agents. The properties and interactions of the TSU-agent are described in Table 5.1.

Next to the geographical demarcation, the TSU-agent is also used to represent learning venues at regional level in Uganda. At these learning venues district come together to share best practices. In the conceptualisation of learning we have seen that it matters at what scale information is shared. The agent that represents regional level therefore plays an important role in the *myopic* replication method. The TSU-agent constructs a list of districts and their performance. The agent ranks the districts and this information is used to support the learning processes of selection and replication. Note that this is only the case in simulations where a scenario is run with a myopic replication method. Otherwise, the ranking is constructed at national level (see section 5.2 about the environment).

Table 5.1. Properties of Regional Level Agent.

Property	Description	Interactions
Number	The TSU in Uganda are numbered 1 to 8	A district belongs to a certain TSU number
Boundaries	Sets the boundaries of the TSUs in the NetLogo World	Graphical representation

Continuation of Table 5.1

Property	Description	Interactions
Colour	Sets the colour of the region covered by the TSU in the NetLogo world	Water points are created on a patch with the colour of the TSU their district belongs to
Regional ranking list	A list of districts and their water quantity delivered	Input for the myopic selection and replication procedures
Regional best district level	The level of water quantity per person of the best performing district in the region	Districts determine their replication procedures based on this level
Regional median district level	The level of water quantity per person of the median ranked district in the region	District determine their replication procedures based on this level
myDistrictList	A list of districts that belong in the TSU	These districts are placed in the TSU and are selected in the myopic replication method
Regional best X, Y and Z	The allocation ratio of the best performing district in the region	Determines what ratio is replicated

5.1.2 District-agent: District Level

The district-agent represents the district level in Uganda. The agent represents all efforts that are concerned with the delivery of water services at district level, for instance by the District Local Government and the District Water Office. The district-agent also includes both service authorities and service providers. Service providers, such as the hand pump mechanics, are considered to operate at an institutional level *below* the district level, for instance sub-county level. However, since the district level is the lowest institutional level considered in the ABM, this level includes those who execute effort to raise water service levels, for instance to install a new water point or to repair a broken one.

The district-agents in the ABM represent real district in Uganda. They are based on the actual district in terms of name, TSU-region, population, number of water points, functionality percentage of water points and available budget in the District Conditional Grant. The district data are gathered via Directorate of Water Development and Ministry of Water and Environment [2016], for name of the district, population in the district, number of water points and functionality percentage, Ministry of Finance Planning and Economic Development [2016] for DCG budget and Watsisi [2016] for the area covered by a TSU. In subsection 5.2.2 a description of the calculations for the Water Service Levels in the districts is provided. The properties and interactions of the district-agent are described in Table 5.2.

Table 5.2. Properties of District Level Agent.

Property	**Description**	**Interactions**
TSU number	A number of the TSU the district belongs to	Determines to what TSU the district communicates in the myopic replication method
Number	All districts are identified with a number	Used to set the right parameters from the table of districts. WP belong to a district number
Name	All districts represent real districts	Communication and understanding purposes
Population	Number of people living in the district	Determines the Water quantity per person
Number of WP	Total amount of WP (both functional and non-functional) in the district	Determines the water quantity delivered
Functionality Percentage	Total amount of WP that are functional as a fraction of the total number of WP	Determines the water quantity delivered
Colour	The colour of the patches of the TSU region	Determines where a district is positioned in the NetLogo World
Water Quantity per person	Amount of water delivered in the district in *litres per person per day*	Determines the ranking of a district
Water Quantity delivered	Total amount of water delivered in the district in litres per day	Determines the ranking of a district
Planned X, Y and Z	Ratio from DCG planned to spend on CapEx, CapManEx and unspent	Determines the amount of money a district has available for CapEx and CapManEx
Actual X, Y and Z	Ratio from DCG actually spent on CapEx, CapManEx and unspent	Is used to distinguish ratio in new year from ratio in previous year for variation method
DCG	District Conditional Grant: total allocation budget received from national level via the DWSCG-formula	Determines the maximum amount of money a district can spend on X, Y and Z
Capex Budget	Amount of budget available for CapEx events	Is calculated from the DCG and the allocation ratio
Capex spent	Amount of money spent on CapEx events	Calculated after CapEx expenditures
Capmanex budget	Amount of money available for CapManEx events	Is calculated from the DCG and the allocation ratio
Capmanex spent	Amount of money spent on CapManEx events	Calculated after CapManEx expenditures

Continuation of Table 5.2

Property	Description	Interactions
Best district?	If 0, district is not the best performing district in the ranking. If 1, district is the best performing district (Boolean)	Determines the ratio that is copied by poor-performing districts
Bottom half?	If 0, district is not in bottom half of ranking, if 1, district is in bottom half of ranking (Boolean)	Determines the allocation ratio a district will select to replicate
Use own ratio?	Represents whether the district is performing good or bad. 0 = bad, 1 = good (Boolean)	When a district performs well, it will use the own ratio in the next year, when it isn't, it will copy one from a district that is
MyWPList	List of WP that are in a district	WP that are created are added to the list. Districts calculate water-quantity-delivered based on this list

5.1.3 WP-agent: Water Infrastructure

The WP-agent represents water infrastructure in the ABM. All water infrastructure is considered to be of the type shallow well with hand pump, therefore, all WP-agents in the ABM have the characteristics of a shallow well. WP are part of the technical system if we represent the system as an STS. Various stochastic processes in the ABM determine the breakdown and lifetime of a WP. The WP are acted upon by the social system. In the ABM the interactions of WP are mainly with the district-agents as they represent the role of service providers. An overview of the properties and behaviours of the WP-agent is represented in Table 5.3.

Table 5.3. Properties of Water Point Agent.

Property	Description	Interactions
Operation state	Defines whether a WP is functional or not. Non-functional = 0 , Functional = 1	Determines if a WP delivers a service. Non-functional WP can be repaired
Age	Years that a WP is functional	Determines a WP breakdown
Non-functioning years	Years that a water point is out of operation	If a water point is non-operational for 5 years in a row it dies
Expected lifetime	Years that a WP is expected to remain functional	Determines a WP breakdown
District number	Corresponds to the district that the WP is in	Determines the water quantity delivered of the district

Continuation of Table 5.3

Property	Description	Interactions
District colour	Corresponds to the colour of the background of the district in the NetLogo world	WP that are made can only be put on patches with this colour

5.2 Parametrisation of Environment and Time

In this section the focus is on the implementation of the environment and the use of time in the ABM. The environment can be separated in two part. The first part concerns all properties and behaviours of the environment that are considered part of the conceptualisation of national level in Uganda. The national level in Uganda is not represented by an agent in the ABM, but is considered to be part of the environment. In the software this means that the national level consists of *global* variables, that every agent can act upon [Wilensky, 2016]. A detailed description of the representation of national level in the ABM is presented in subsection 5.2.1. The second part of the environment is mainly concerned with calculations. These calculations are needed to for example implement the learning processes, or to assign the right values to certain variables. In subsection 5.2.2, therefore, a detailed set-up of everything that is considered in the ABM that is not an agent nor part of the representation of national level. In the third part of this section the implementation of time and the most important model procedures are described.

5.2.1 Environment: National Level

The national level of Uganda is represented in the ABM as part of the environment, hence there is no *national-agent*. A number of global variables relate to the national level. First the national level dictates the districts the boundaries of the allocation ratio for CapEx and CapManEx. Second, the target water quantity for districts is a policy set at national level.

The national level also has a role in the implementation of the learning algorithms. In case of a fully rational and a random replication method the national level constructs a ranking list of the performance of the districts is constructed at the national level. With this ranking the allocation ratio of the best performing district is determined for the replication process and the bottom half of the districts is determined for the process of selection. An overview of the properties of national level is shown in Table 5.4.

Table 5.4. Properties of National Level.

Property	Description	Interactions
Minimum CapEx Percentage	National set policy determining the minimum percentage of the DCG that is to be spent on CapEx	Determines the boundaries of the allocation ratio
Maximum CapManEx Percentage	National set policy determining the maximum percentage of the DCG that is to be spent on CapManEx	Determines the boundaries of the allocation ratio

Continuation of Table 5.4

Property	Description	Interactions
Target Quantity	The target level in litres per person per day that a district should reach	Determines whether a district is performing good or bad, important for selection and replication procedures
National ranking list	A list of districts water quantity per person	Input for the fully rational selection and replication procedures
National best district level	The level of water quantity per person of the best performing district	Districts determine their replication procedures based on this level
National median district level	The level of water quantity per person of the median ranked district	Districts determine their replication procedures based on this level
National best X, Y and Z	The allocation ratio of nations best performing district	Output variables

5.2.2 Detailed ABM set-up

In the agent parametrisation and in the parametrisation of the national level the properties and interactions in the model are described. For the initial set-up in the ABM we need to assign numbers to some of these variables. An overview of how the variables in the model are parametrised is given in Table 5.5. As many numbers used in the ABM are assumptions, the source of the assumption is added.

Table 5.5. Model Parametrisation.

Parameter	Units	Value	Source	Comment
Number of Districts	-	110	Directorate of Water Development and Ministry of Water and Environment [2016]	Kampala District has no rural characteristics
Delivery Capacity Water Point	Litres per day	6000	Directorate of Water Development and Ministry of Water and Environment [2016, F.A.Q.], Biteete et al. [2013, p. 24]	All are shallow well with hand pump
Population growth rate	% per year	3.6	Biteete et al. [2013, p. 1]	
Target Quantity	Litres per person per day	20	Biteete et al. [2013, p. iv]	

Continuation of Table 5.5

Parameter	Units	Value	Source	Comment
CapEx price	USD	2300	Biteete et al. [2013, p. iii]	
CapManEx price	USD	600	Biteete et al. [2013, p. iii]	
Mean lifetime Water Point	Year	6	Moriarty [2016]	
Standard Deviation Lifetime Water Point	-	1.5	Moriarty [2016]	
Simulation Years	Year	20		

Two situations in the ABM need a more detailed description, as their calculations are both complicated and important to understand. Both calculation are also described in section A.2, but since they are important a description in words is added here. The first is the calculation of water quantity per person in the ABM. This calculation is important for the selection process, where we determine *good* and *bad* performance. The initial parametrisation of water quantity in the districts in the ABM is based on the actuals in Uganda. There are data about water infrastructure in Uganda available via Directorate of Water Development and Ministry of Water and Environment [2016]. This database contains information about how many water points of a certain type of infrastructure there are in every district and how many of them are operational. Second, the source uses assumptions about how many people can be provided with a certain type of infrastructure. For instance: a spring source is assumed to deliver 20 litres of water per day for a total of 200 persons. The amount of functional water points of every type in a district is multiplied with its assumed delivery capacity. This results in a total litres of water delivered in a district. This is used for two things: 1) calculate water quantity per person by dividing the total amount of water delivered by the population, and 2) calculate the number of Water Points of the type that we consider in the ABM. All water infrastructure in the model is assumed to be a shallow well with a hand pump. According to Ministry of Water and Environment [2015, Annex IV] the delivery capacity of a shallow well with a hand pump is sufficient to provide 300 people with 20 litres of water per day. The total amount of water is divided by the delivery capacity of a shallow well, to get to the number of functioning wells (WP-agents) in the districts (district-agents) in the ABM. Next, the total number of wells is calculated by considering the functionality percentage of the district, which data are also available at Directorate of Water Development and Ministry of Water and Environment [2016]. These were calculation for the initial conditions. During the simulation similar calculations are made. This time only to calculate the water quantity to track the performance of the districts. The calculation of water quantity is made by multiplying the number of functional water points with their assumed delivery capacity and divide that by the population in the district.

The second important calculation considers the variation process. In the variation process we choose between making a perfect copy or adding some variation to the selected allocation ratio. The latter represents both the unconscious process of making a mistake while copying the ratio and the conscious process of adjusting a selected ratio to the own situation. For the addition of variation a calculation is made. We consider an *old* ratio - the ratio the district used in the previous tick - and a *new* ratio - the ratio the district has selected through the processes of selection and replication to use in the next tick. We consider only the ratios for CapEx and CapManEx in the formula (the ratio for unspent budget is always a result of the both). First we deduct the ratio for the old CapEx of the new CapEx ratio. Second we take a random number between the difference and 0. This number is firstly deducted from the new CapEx ratio, and, hence, added to if the first step returns a negative number. The same number is the added to the ratio for CapManEx.

5.2.3 Time and procedures

For the implementation of time in the ABM we have to consider the smallest time step and the period over which we simulate. First, considering the smallest time step or the *tick* in the ABM, remember the heuristic to take the smallest time step of interest. In this case I have chosen for time steps of a year. In a time step of a year, all dynamics and granularity of events in a year is aggregated. We are interested to observe the result of how policies are transferred between districts and how it influences the outcome of system behaviour and a year should give us the right time scale as the policy of interest in our ABM is considered at a yearly basis.

Second, considering the total simulation time of the ABM, remember the heuristic to take the longest time period of interest. Simulations with the ABM are ran over a period of 20 years. The average lifetime of a water point is 6 years, meaning that we are able to observe a period of 3 to 4 infrastructure life cycles. We want to be able to see the effect of different ways of learning over a period of time that is long enough to observe the effect. Observing 3 to 4 infrastructure life cycles enables us sufficiently to see patterns emerge in the simulation that are not caused by the life-cycles of infrastructure.

In the 20 years of a simulation a number of steps and procedures are repeated every tick. Next, the actions of the agents and the order in which they are performed every year is described. From the actions and interactions between agents in the ABM we are able to observe emergent patterns of system behaviour. Below, I describe what actions are performed. A more detailed description in the form of a model narrative is described in section A.1. A model narrative is still two steps away from coding an actual ABM. The step in between, pseudo-code, is shown in section A.2. The pseudo-code is interesting for people who have experience with coding, but not necessarily with the software that is used: NetLogo [Wilensky, 2016]. The model follows the following procedures:

Return budgets: All residual budgets of the districts from the previous year are returned to national government. The budget that is returned is the cumulative of unspent budget, i.e. budget that is not spent on either CapEx or CapManEx.

Calculate Water Service Levels: All districts calculate the water service level per person in their area. This is a function of the number of water points, the functionality percentage of the water points, the delivery capacity of a water point and the population. The water service levels per person are used to construct the ranking for the selection procedures. We assume that district have full information about the state of the infrastructure in their own area.

Selection processes: In these procedures all districts are ranked according to their water service level per person. We look ahead at the method for replication at this point: if the districts are considered fully rational, the ranking is made at national level, including all districts. If the districts are considered to by myopic, the ranking is made within regions. Hereafter, the districts make three decisions: are they 1) the best performing district and 2) in the bottom half of the ranking, and 3) do they perform above national set target quantity? The first decision is used in the replication procedures. The second and third decision form the selection mechanism: the allocation ratios of district in the bottom half or below target quantity *cease to exist*, the ratios in the top half of the ranking and above target quantity *live on*.

Replication processes: Districts whose allocation ratio *lives* replicate this ratio and use it again next year. Districts who's allocation ratio ceases to exist replicate the allocation ratio that is used in the previous year by the best performing district, i.e. the top ranked district. They replicate either the ratio of the best performing district in the nation (method: fully rational), the ratio of the best performing district in the region (method: myopic), or the ratio of a random other district (method: random).

Variation processes: Only districts who have replicated an allocation ratio of another district follow this procedure. If the variation method is *perfect copy*, the districts blankly imitate the ratio they selected to replicate. If the variation method is *random fractional*, the districts move a random fraction from the ratio they used in the previous year to the ratio they have selected for this year. Thereby, variation is added to the evolution of the allocation ratio.

Ageing of district and water points: First, the population of the districts grows. The population grows with the population growth rate. Second, when operational water points age, they add a year to their age. When they reach their calculated expected lifetime they fail and become non-operational. The counter for non-functional years start at 0. When non-operational water points age, they add a year to their non-functional years. When this counter reaches 5, the water point is considered abandoned and the WP-agent dies.

Districts calculate budgets: All districts calculate their budget for CapEx from the allocation ratio multiplied with the budget in the District Conditional Grant. A similar procedure is followed for CapManEx.

Districts spend CapEx: Districts spend all budget available for CapEx. They determine the maximum amount of water points that can be constructed and create that amount of water points. The water points start delivering services to the districts. Districts calculate how much budget they have spent. The residual budget is transferred to CapManEx.

Districts spend CapManEx: Districts calculate how much water points they are able to repair within CapManEx budget and will repair the maximum number of water points. Any unspent CapManEx is transferred to the *unspent budget*.

5.3 Model Implementation and Verification

The ABM is constructed according to the conceptualisation in chapter 4 and the specification in section 5.1 and section 5.2. A detailed description of the implementation of the model procedures in the ABM is described in appendix A. In this section I briefly show how the model works using the model interface.

Second, I describe the verification of the ABM. I implemented the conceptual model about how learning occurs in rural Uganda into modelling software. For this I used numerous assumptions, calculations and lines of codes. All kinds of mistakes are possible in this process, mistakes that alter the output of the ABM. In the verification of the ABM I show the trustworthiness of this particular implementation. While trusting that the implementation is correct we can go on to experimenting and interpreting the outcomes in respectively chapter 6 and chapter 7.

5.3.1 Model Interface

In Figure 5.1 the model interface is presented. In the interface there are 8 regions represented. Every TSU-agent is visualised by a government building. The area that is covered by the region is identified by colour. In every region there are districts and water points. The agent representing a district is placed at a random location within the region and has the form of a house - this is similar to the houses in section 4.2 that are used to explain the processes of selection, replication and variation. The houses in the initial situation have a blue colour, when the model runs and ticks pass, the houses change colour, according to the performance of the districts determined in the selection procedures. The district is yellow when it is the best performing district, red when it is performing below national target quantity or in the bottom half of the ranking, and the district is blue if it is neither of the previous. Furthermore, there are water points in the visualisation, represented by blue or red water drops. A blue drop represents a functional water point, a red water point is not delivering any water services. The water point are not placed in the proximity of the district they belong to, but they are placed within the region that the district belongs in - this has no particular meaning, it is a convenient implementation in the software.

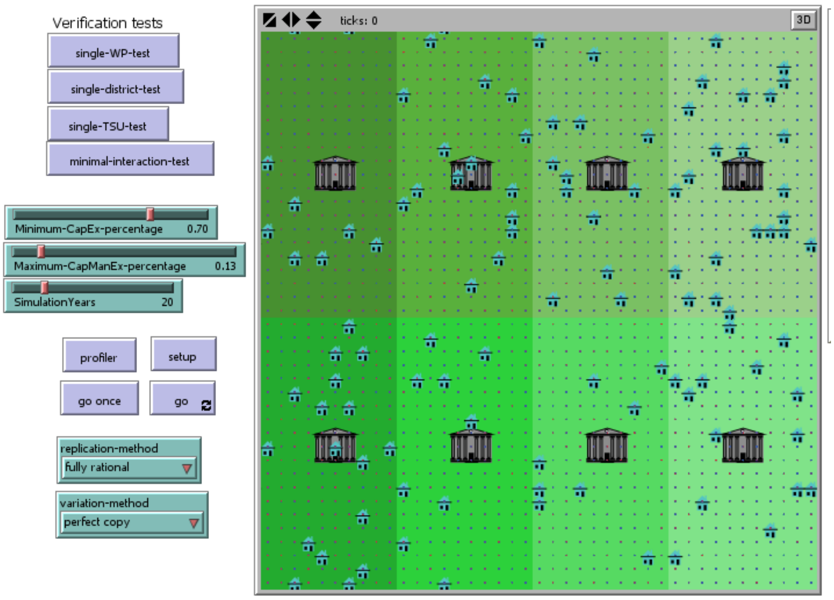


Figure 5.1. Interface of the ABM. A graphical representation of 8 regions (government buildings) with 110 districts (houses) and many more water points (water drops). On the left a set of buttons that call different verification tests is shown. Below there are three global parameters that you can alter in the initial model conditions (Conditions for CapEx and CapManEx, Simulation time). Below that two choosers for the replication method (fully rational, myopic, random) and variation method (perfect copy, random fractional).
.

Left of the visualisation there are buttons for the verification, three sliders, four buttons and two drop-down choosers. The sliders enable change in initial model conditions of three variables. In the interface you can change the boundary conditions for CapEx and CapManEx that are set by national government. In chapter 7 I argue for the presence and use of the sliders. Next, also the simulation length can be adjusted, this allows to quickly simulate scenarios over a longer (or shorter) time period.

The four buttons can be used to set-up and run simulations. The *go-once* button allows to simulate one tick, whereas the *go* button simulates until it reaches the number of Simulation Years. The profiler button is not interesting for one interested in the outcomes of the model. The modeller can use it to explore in what model procedures most computational efforts are needed.

With the two drop-down choosers you can set replication method and variation method. These are used to create different scenarios. More about the scenarios is explained in the set-up of the experiment in chapter 6. For replication method you can select either *fully rational*, *myopic*, or *random*. In succession these represent national, regional and inter-district learning as described in section 3.3 and in subsection 4.2.2. For variation method you can select either *perfect copy* or *random fractional*. These are explained in subsection 4.2.3.

5.3.2 Model Verification

The buttons at the top left of Figure 5.1 are for verification purposes. Reproducible verification tests can be started with the buttons. There are four different verification tests. The four test are designed to verify every model procedure: does the procedure do what it is intended to do? What we want to prove is that you can trust the implementation of the conceptual model into the ABM software. When we are sure to trust the implementation, we can go ahead into experiments and interpreting the model results, because we know the implementation is correct. The set-up of the verification follows the basic verification steps that are described by Dam et al. [2013]. The tests are performed in a *predictable* environment. In contrast the default model behaviour, outside of the verification test, is designed to let behavioural patterns *emerge*. Inherent to emerging behaviour are unpredictable outcomes. Because we want to verify if the procedures are implemented correctly, the verification is performed in a predictable environment. In total a number of four tests are performed. First we do three *single agent tests*. In these tests we verify whether the procedures work as intended by the modeller. We first test a single water point in his environment to see whether the simplest procedures are correct. Then we add slight complexity to the model, by first testing a single district with multiple water points and second testing a single TSU with multiple district that all contain multiple water points. Finally, in a *minimal interaction test*, we test the interactions between two regions, as this allows us to verify the implementation of the learning algorithms. In this section the four test - 3 single agent test and 1 minimal interaction test- are described. The figures show the interface and the output of every test in the ABM. The output is generated in the command centre of the Netlogo software and is the result of the piece of code that verifies the procedures in the ABM. If a procedure does not result in the expected behaviour the command centre shows an error. The tests are reproducible, meaning that you can perform them again when in the Netlogo environment.

In the first verification test, the *single-wp-test*, the model procedures are tested with a single water point. The water point is placed within a district and the district is placed within a region. Since we have a

(a) Interface single WP test

```
Single WP Test

Confirmed: water quantity per person correct
Confirmed: best district correct
Confirmed: bottom district correct
Confirmed: use own ratio correct
Confirmed: replicate meme correct
Confirmed: variate meme correct
Confirmed: population grow correct
Confirmed: age-and-fail correct
Confirmed: capex-budget calculation correct
Confirmed: capmanex-budget calculation correct
Confirmed: spend-capex correct
Confirmed: residual capex transferred correct
Confirmed: spend-capmanex correct
Confirmed: update ratio correct
```

(b) Command center: verification of procedures

Figure 5.2. Verification: output of single water point test

predictable environment the parameters are predetermined: the water point serves a district population of 300, resulting in an initial water quantity of 20 litres of water per person per day. The initial allocation ratio of the district is 0.70:0.13:0.17. In Figure 5.2 the output of the test is shown.

All procedures in Figure 5.2 are marked *Confirmed*. They are in their current state, but in the process of verifying I encountered some implementation errors. The errors were identified and solved in the following procedures:

choose-use-own-ratio: Districts that are marked 'best-district' do not use their own ratio if they fail to deliver the target water quantity. Fixed by adding ifelse-condition that checks if a district is the best performing district.

variate-meme: Districts that are marked 'best-district' vary their allocation ratio, whereas they shouldn't. This was fixed by adding an ifelse-condition that checks if a district is the best performing district.

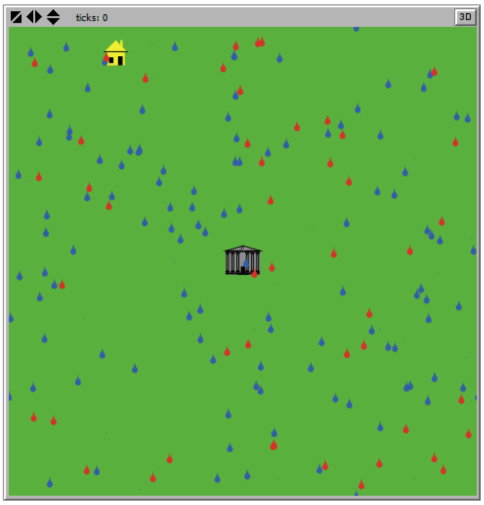
calculate-DCG: Districts would receive a negative budget if they perform (far) above target-quantity. Result of a non-accurate implementation of the official formula. The condition that the budget may not be lower than the budget in the previous year is added. The decision is made to work with another implementation of DCG as is described in this thesis.

In the second verification test, the *single-district-test*, the performance of a single district is tested. The number of water points in a district is bigger than 1, in contrast to the previous verification test. We are slowly adding more complexity and more interactions to the model to verify if the procedures are still correct. Again, this is a controlled environment where we test if procedures result in some expected output. The district is set up with 160 water points of which 75% are operational, serving 50000 people. The district is placed within a TSU. The single district test is again a verification of all basic model procedures. The output of the test is shown in Figure 5.3.

In the figure interface we firstly observe multiple water points in a district in a region. Second, in the output of the command centre we see that all procedures are confirmed. Some slight alterations had to be made however:

calculate-water-quantity-per-person: Sign determining the operation-state of WP was $<$, where it should be $\leq$, otherwise it results in 1 water point too little. This was fixed by changing the sign.

spend-capex: Newly constructed WP had no operation-state. This was fixed by setting operation-state of new WP.



(a) Interface single district test

```
Single district Test

Confirmed: water quantity per person correct
Confirmed: all selection procedures are correct
Confirmed: replication and variation procedures correct
Confirmed: population grow correct
Confirmed: age and fail correct
Confirmed: capex and capmanex calculation correct
Confirmed: spend-capex correct
Confirmed: transfer residual capex correct
Confirmed: spend-capmanex correct
```

(b) Command center: verification of procedures

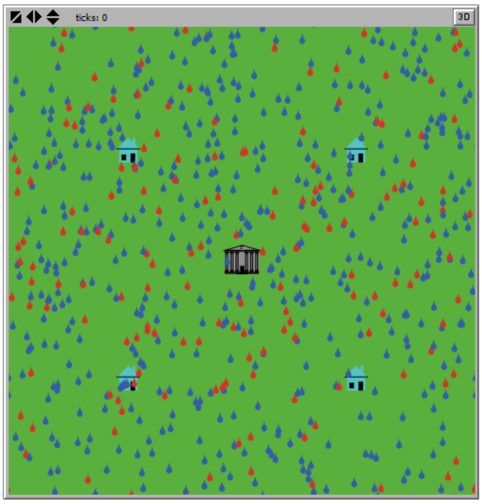
Figure 5.3. Verification: output of single district test

At this point we can trust the implementation of most of the procedures in the ABM. We have seen that for two simple simulations the ABM returns all predictable outcomes. However, up to this point we tested no more than one district, therefore we were not able to be sufficiently confident about the implementation of the procedures that describe the evolutionary processes of selection, replication and variation, as we need multiple districts for those. In the next two verification test we focus on the implementation of memetics.

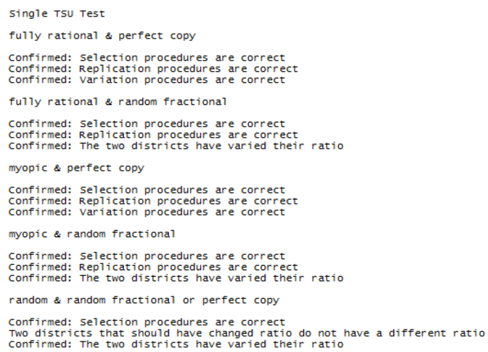
The third verification test is a test with a single TSU, the *single-TSU-test*. A single TSU is set-up with four districts who all have a predefined number of water points. Since this set-up enables to verify the exchange of allocation ratios the selection, replication and variation procedures are verified. The output of the test is shown in Figure 5.4. In the test the procedures for the three evolutionary processes are verified under all combinations for replication-method and variation-method.

The test showed one slight problem. As can be seen in Figure 5.4b the procedure with random replication method and random fractional variation method is hard to verify. If the variation-method is random, a step is made between the ratio used in the previous tick and the ratio selected for the next tick. The implementation of this method allows the step to be 0, resulting in an identical allocation ratio. I did multiple tests to verify the workings of this step and I am confident it works as I intended it to work.

The fourth and last verification test, the *minimal-interaction-test*, is focussed on the interaction between different TSU-agents. The previous verification step allowed for analysis of the implementation of the processes of selection, replication and variation, except for one combination. In the replication process we determine at what scale the districts exchange information. If one TSU-agent is considered, the fully



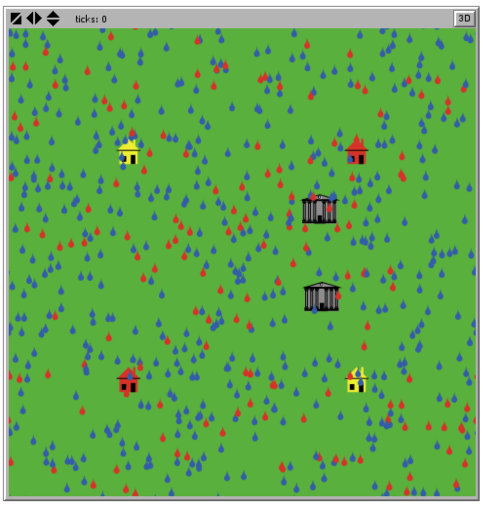
(a) Interface single TSU test



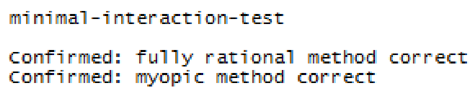
(b) Command center: verification of procedures

Figure 5.4. Verification: output of single TSU test

rational method and the myopic method result in similar outcomes. Therefore, we now test if these processes are implemented correctly. The output is shown in Figure 5.5 and shows that the procedures are implemented correctly.



(a) Interface minimal interaction test



(b) Command center: verification of procedures

Figure 5.5. Verification: output of minimal interaction test

Through these tests and solving the problems encountered I am confident that the conceptual model of learning in rural Uganda is implemented in the software in a correct way. Through a series of four tests all model procedures and interactions are tested in a predictable environment. The thesis is up to the point where I can design an experiment to do simulations with the model, the set-up of the experiments is described in the next chapter. Besides, this chapter showed how the conceptual model is implemented in the ABM.

6 | Experiment Design

In this chapter the design of the experiments is described. So far in this thesis, we have seen a conceptual model of learning in the rural water supply sector in Uganda in chapter 4, we have seen how that conceptual model is implemented in an ABM (section 5.1, section 5.2) and we have seen a verification of the implementation of the ABM (section 5.3). This part describes what experiments are performed with the ABM and how these can contribute to understanding how learning in a water supply system can take place.

The interest of this thesis goes out to learning in rural Uganda and the effect of learning on water service levels and therefore learning is subject of the experiments. Learning is conceptualised and implemented using the theory of memetics. In memetics evolution of information is described through the processes of selection, replication and variation. We applied the theory by identifying a *meme*, a piece of information that evolves, in the rural water supply sector. This meme is the *allocation ratio* that districts use, representing a policy choice at district level. The processes of selection, replication and variation enable us to see an allocation ratio evolve through the rural water supply system. The experiments focus on different conditions for the evolution of the allocation ratio and therefore different representations of learning in the sector, as they are identified in section 3.3.

The first step to implement the process of selection in the ABM was to identify a performance indicator for the allocation ratio. This performance indicator is the water service level of the district that uses the allocation ratio, measured in water quantity per person. Next, for the selection procedure, two criteria are used to judge how well an allocation ratio performs. First, a ranking is constructed of all districts based on their water service level, ranked from highest to lowest. Second, the national target water quantity is used as a threshold value for good performance. The selection process is implemented as described above and there are no different scenario possibilities created for this process. Therefore, the selection mechanism is used in the same way in every experiment.

We are able to explore different scenarios for the processes of replication and variation though. The replication process contains valuable conceptualisations of learning in the rural water supply sector. Three different ways of learning are identified in the sector, each one with a different number of institutional levels involved. The three ways of learning are inter-district, regional and national. They represent via what institutional levels districts can learn about a policy from each other. In the implementation of the replication procedure these concepts of learning are translated to three different methods of replication. First, the learning alternative via the national level is represented by a method where districts are fully rational, meaning they are aware of the state of all other districts. The ranking in this scenario is made at the national level to account for the full rationality. Second, the regional learning alternative is represented by a replication method where the view of the district is myopic, meaning they are able to observe only the districts that are within their region. Third, inter-district learning is considered by a replication method that is random. Districts communicate with a random other district. The experiment set-up includes the three replication methods, as it enables us to observe the aggregated behaviour at system level of three different conceptualisations of how learning occurs in the Ugandan rural water supply system.

The variation process includes two conceptualisations of how an allocation is varied once it is replicated by a district. In the first variation method no variation is added to the ratio. Districts make a perfect copy of the allocation ratio they replicate. In the second method, districts slightly adjust the ratio. They adjust it with a random fraction towards the allocation ratio they used themselves in the previous year. The second method represents either a slight communication error between districts or the rational choice of a district to adjust the ratio to their own situation.

The experiment is set-up with the processes of selection, replication and variation. All different methods are combined with each other into a set of scenarios. The experiment tests if different methods for replication and variation result in different system behaviour and result in different water service levels in the rural water supply sector in Uganda. All methods are combined with each other in the different scenarios. An overview of the experimental design is shown in Table 6.1. As can be observed in the table, the matrix does not lead to 6 different experiments as you would expect with 1 (selection) times 3 (replication) times 2 (variation) methods. The implementation of the random replication method is done in such a way that a district chooses an allocation ratio from a random other district. Adding or not adding a random amount of variation to this random process does not lead to different outcomes and is in essence the same. Multiple simulations that are done with the two combinations of methods also show that these processes result in similar outcomes. Therefore, the two variation methods for the random replication method are considered as one scenario.

Table 6.1. Design of the Experiments

Variation method / Replication method	**Perfect Copy**	**Random Fractional**
Fully Rational	Scenario 1	Scenario 2
Myopic	Scenario 3	Scenario 4
Random	Scenario 5	

In total a number of 500 simulations are performed with the ABM - a hundred for every scenario. There are stochastic processes in the model, such as water point failure or the initial allocation ratio of the districts, meaning that we should do multiple simulations of the same scenarios to be confident about the average behaviour of the system. The simulations are run using the *Behaviour Space* function in Netlogo. Behaviour Space is an environment to set up simulations and determine output variables. Many output variables are gathered in the simulations, including outputs to analyse district performance, regional performance and performance aggregated at national level. The analysis of the output of the experiments is presented in the next chapter.

7 | Results of the Experiment

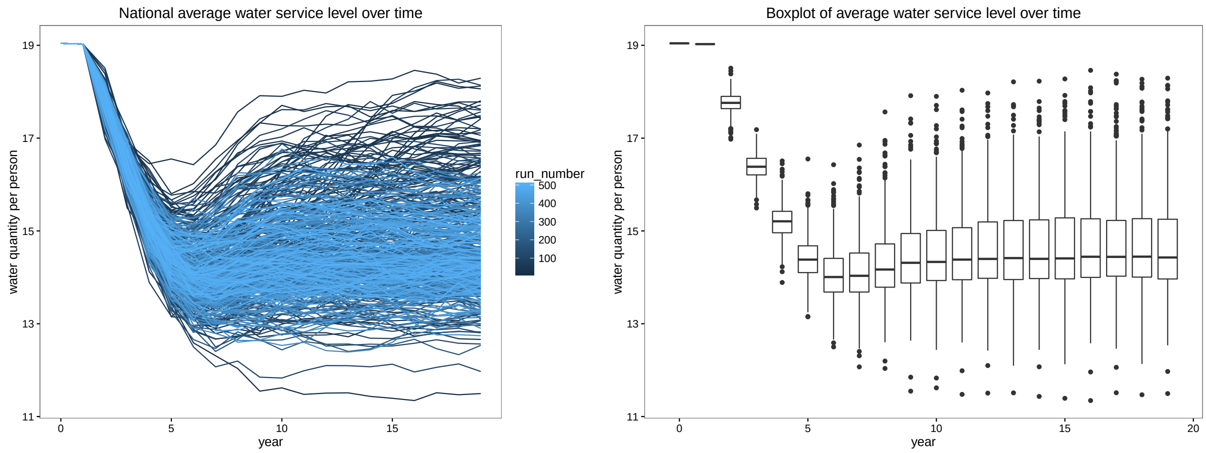
In this chapter the results of the experiments are discussed and interpreted. The main focus of the analysis is on the experiment described in chapter 6, which is set up to analyse how the different scenarios for the use of memetics influence the behaviour and output of the system. An analysis and interpretation of the scenarios for the replication and variation processes is described in section 7.2. However, first we turn our attention to the observed behaviour in the ABM in general. The emergent behaviour deserves, as I will show, some critical appraisal. The general behaviour of the simulations and some important considerations about this behaviour are described in section 7.1.

Besides the general system behaviour and an analysis of the experiment, the data analysis also provides some insights into the policy of interest in the simulations: the allocation ratio. In the current implementation of the policy the districts are bound by the Ministry of Water and Environment (MWE) to invest their budget mostly in CapEx, because the MWE aims to raise the percentage of coverage in the district. In section 7.3 I argue that the current restrictions by the MWE are hampering progress on water service levels in the districts. I describe how the simulations show a higher percentage of functionality, a higher total number of water points and a higher average service level in the case of loosened restrictions for CapEx and CapManEx.

7.1 Analysis of Emergent System behaviour

In first instance we look at the general behaviour of the simulations. We are interested to see what patterns emerge from the interactions between the districts, the TSUs and the Water Points. The model behaviour is expected to behave stable at district level, as the financial allocation from national level to district level is assumed to grow with the same rate as the population growth. The extent to which the initial budget allocation represents a valid amount for each district is disputable, as it is based on the the allocated budget to the district in the Financial Year 15/16. This budget is not necessarily representative over time for a district. The behaviour that is expected is stable in the sense that I expect the districts to come to a certain attractor value, where a balance between investments and infrastructure failure is found. I expect to see different attractor values based on the different methods for learning, but more on that in the next section.

To observe the general system behaviour a visualisation is made that shows the average performance of all districts for every simulation. This is shown in Figure 7.1a. Every line in this figure shows the average water quantity of 110 district over a period of 20 years. Every line furthermore represents one simulation, therefore 500 lines are drawn in the figure, each representing one simulation run. What we see is that in the first 5-6 years the average performance of the districts in all simulations shows a steep drop from about 19 litres of water per person to 13-16 litres of water per person. After the steep drop the system stabilises. Before we go into detail analysing both the drop, the reason for stabilisation and the level of stabilisation, we first consider the spread of the runs. In the first 5 years the simulations stay close to each other, after that they spread from 12 to 18 over a period of 20 years. Around a water quantity of 13-15 the simulations seems to be more dense. To be sure a box plot of the system behaviour is added in Figure 7.1b. The box plot shows where most of the simulations are. In the box plot we can see that the hypothesis is confirmed and most of the simulations stabilise around a water quantity of 14. We furthermore see that a little number of runs end up at the extremes of the graph, around 12 and 18.



(a) Average national performance of all simulations

(b) A Box plot of the average performance

Figure 7.1. Average performance of 500 simulation runs over time. One line represents the average water service level of 110 districts over a period of 20 years in one simulation run

First of all, let us interpret what the levels in the simulations mean. The initial conditions in the simulations show a water quantity level of approximately 19 litres of water per day, compared to the national target of 20 litres of water per day. The model behaviour furthermore stabilises after 5 years at approximately 14-15 litres of water per person per day. The national *coverage* in Uganda is estimated at 65% [Ministry of Water and Environment, 2015]. In the conceptualisation of the water service level in the ABM, this would result in a water service level of 13-14, if a 100% would be 20 litres of water per person per day. However, the performance indicators national coverage and water quantity delivered per person are *different*. The indicator used in the ABM considers aggregate district behaviour, whereas the coverage indicator considers lower institutional levels as well. This shows that it is difficult to compare both indicators of performance to each other, let alone if the service level in the simulations is a good representation.

Let us now consider both the steep drop from the initial conditions and the stable behaviour after 5 years. First of all, the stable behaviour can be extrapolated over a long period of time. I've tested up to 100 years and observed stable behaviour over time in all simulations. The hypothesis is that the steep decline is an artefact of they way the system is modelled, rather than a behaviour that is to be expected in the actual system. The initial conditions of the model are based on the actual situation in Uganda. The district-agents in the ABM are similar to the districts in Uganda in terms of anything that matters for the water quantity level: population size, total water quantity delivered in the district, the functionality percentage of the water points and the delivery capacity of a water point. All data are retrieved from government sources that are used to monitor progress in rural Uganda [Directorate of Water Development and Ministry of Water and Environment, 2016].

For a moment we assume that the initial conditions are correct and the level of stabilisation is too low. Abstracted to a simpler representation, a stable level means that the districts spend just enough budget to keep up with both infrastructure breakdown and population growth. Since the budget of the districts grows with the same rate as the population growth we will further assume that the budget of the district and the infrastructure breakdown are in balance. Note that we leave the analysis of the investment strategy of districts to the next section, where we analyse how districts learn from each other about the policy for investments. The failure of infrastructure in the simulations is an artefact of some conceptual and numerical assumptions, such as the distribution of expected lifetime of water points and the investment costs for CapEx and CapManEx. The budget of the districts in the simulation is an artefact of assumptions about the District Conditional Grant (DCG) and the growth of this grant. Important is that either of these assumptions can have a large effect on the level at which the both are in balance. The water supply sector is financially intensive and in the ABM this is no different. In an extra experiment the sensitivity of the level at which the simulations stabilise to the initial budget of the districts is tested. The test is visualised in Figure 7.2. The figure shows how sensitive the output of the model is to changes in the initial DCG budget. The DCG budget of the districts is varied with -10%, -1%, 0%, +1% and +10%. For each scenario the output of a total of 20 simulations after 20 years is shown. The figure thus only shows where the simulations end, not their behaviour over time as the previous figures did.

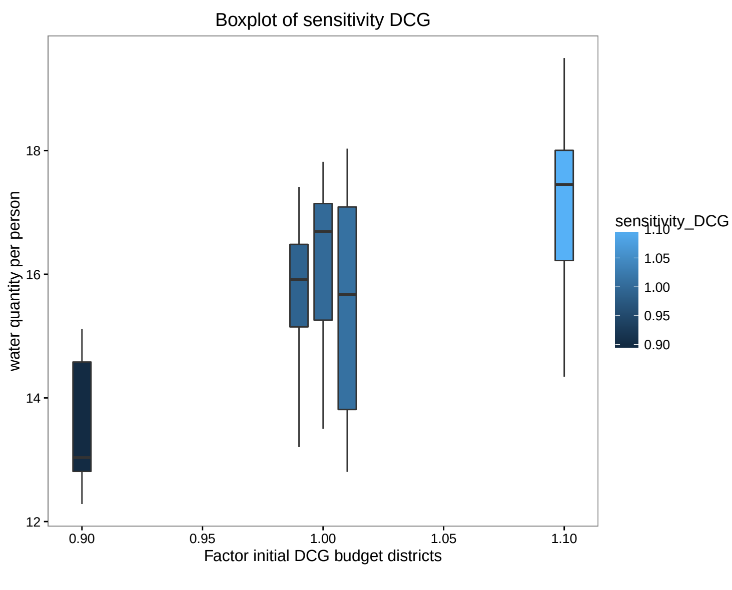


Figure 7.2. Sensitivity analysis of model behaviour to initial budget districts. The initial budgets of the districts are multiplied with the factor in the x axis. The boxes show the outcomes of all runs after a period of 20 years.

We see the five box plots of the five scenarios for DCG budget show that the more budget the districts receive, the higher the runs end up. The centre three plots do not show the behaviour that you would expect given the outer two plots. Each of the runs is based on 20 simulation runs, which is not enough to get a good representation with a difference of 1%. If we compare the most extreme scenarios the median of the simulations end up around a median water quantity of 13 when the districts receive 10% less budget and around a median water quantity of 17.5 if the districts would receive 10% more budget. This does not necessarily mean that the assumption for the DCG budget the districts receive in the model is wrong, but it shows that the model behaviour is very sensitive to the assumptions about financial parameters. Considering the level at which the model becomes stable, there are more parameters that can have similar influence, such as the parameters for the water infrastructure in the ABM. Again, this does not have to mean that the parametrisation of the ABM is wrong, but rather the realisation that all parameters can influence this level and, as such, the level at which the system behaves stable is an artefact of the parametrisation. Furthermore, I should state that we don't intend to use the model to predict a future state of the Ugandan rural water supply system. Instead, we intend to use is to explore possible futures and observe what variables play what role in what possible future.

In the previous part we assumed the initial conditions of the districts were correct. We now revisit this assumption and consider why the initial conditions might be wrong and explain the quick descent in the first five years. A fair consideration is the correctness of the input data in the model. The data of the districts originate from Directorate of Water Development and Ministry of Water and Environment [2016]. Some assumptions are present in these data as well. Ugandan governments use heuristics to determine how many people are served by a water point, e.g. a shallow well has the capacity to deliver 300 people an amount of 20 litres of water per day [Ministry of Water and Environment, 2015, Annex iv]. I have implemented these heuristics in the calculations of the ABM, if these are inaccurate, the initial conditions in the ABM are inaccurate as well.

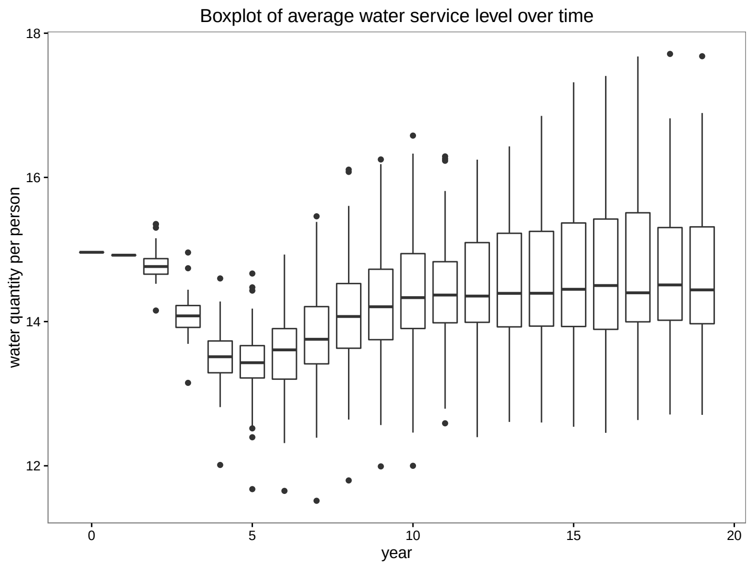


Figure 7.3. Test with district output as input in the next simulation

One more test is performed to verify whether the steep decline of the average performance is a model artefact. In this test the water service levels of the districts at the end of one run, are used as an input for another run. This results in a situation were the districts start at the level were they became stable in the previous run. The implementation is not as straightforward though, as the districts developed over a period of 20 year and the number of water points and the population grew accordingly. The water quantity delivered in a district is a sum of the population, the total number of water points and the functionality percentage of the water points. In the test the number of water points is varied compared to the original initial conditions to get to the water service level they reached at the end of the previous run. Another implementation could have been to vary the functionality percentage of the water points in every district to get to the right water service level. A total of 50 simulations are performed with the ABM, 10 for every scenario for replication and variation to have a similar representation as the general model run. This resulted in the box plot shown in Figure 7.3.

It is interesting that we observe the same behaviour in this figure. The initial conditions of the districts are lower than in the original situation: 15 in this run compared to 19 in the original simulations. After this, the median of the average performance of the districts declines to almost 13 in 5 years. Next, the median grows to about 14 in the next 5 years. We can now conclude that the steep decline is not caused by too high or too low conditions. The hypothesis that the steep decline is a model artefact is not yet confirmed, but can not yet be denied either. I explained how the initial conditions of the run are implemented: by changing the number of water points in every district. An implication of this choice is that the functionality percentage of water points in the district is not varied. Additional simulations with the ABM show that the decline of average district performance is similar to the decline in average functionality percentage of the districts. The decline in functionality percentage is caused by the fact that many water points break down in the first few years, quicker than they are repaired apparently. This process is shown in Figure 7.4.

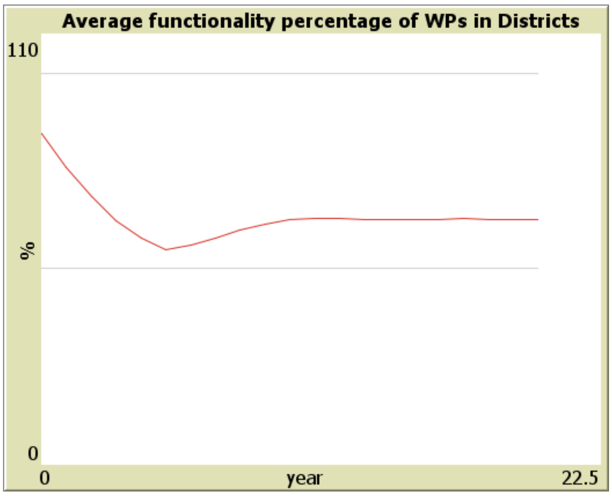


Figure 7.4. Average functionality percentage of the districts in a single simulation. The red line represents the average functionality percentage, whereas the grey lines are supportive for interpretation representing a 100% and 50%.

The figure shows the average functionality percentage of the water points in all districts. In the initial conditions this is approximately 84%. Hereafter is decline to approximately 55% in 5 years and climbs back up to about 63% in 10 years. This behaviour is similar to the behaviour of the average performance of the districts. Does this mean that the observed is a model artefact rather than the real expected behaviour? The answer is twofold. Yes, it is a model artefact, as the assumptions for DCG budget of the districts and assumptions about the water infrastructure, such as price and lifetime, determine if districts have enough budget to maintain the situation. The second part of the answer, however, stipulates the fact that these results are indicative for a wrong investment strategy. The districts start at a certain water service level, with a certain functionality percentage of their water infrastructure. The budget they receive together with the policy they use to spend it results in the fact that the levels cannot be maintained. We know that a repair is less costly than the installation of a new water point and a possibility is that the budget for maintenance is too little to maintain current service levels. In section 7.3 this suggestion is discussed in more detail. Lastly, this finding can also mean that there are other sources of budget in the system for the districts that are not represented in the ABM. This could be for example donor help, those sort of projects are kept of the records and this could cause that there is not enough budget for CapManEx in the ABM to maintain the functionality percentage of the initial conditions. With the disincentives provided by the budget allocation formula of national level for districts that perform above national average this is a relevant suggestion. However, there is no evidence to support this claim.

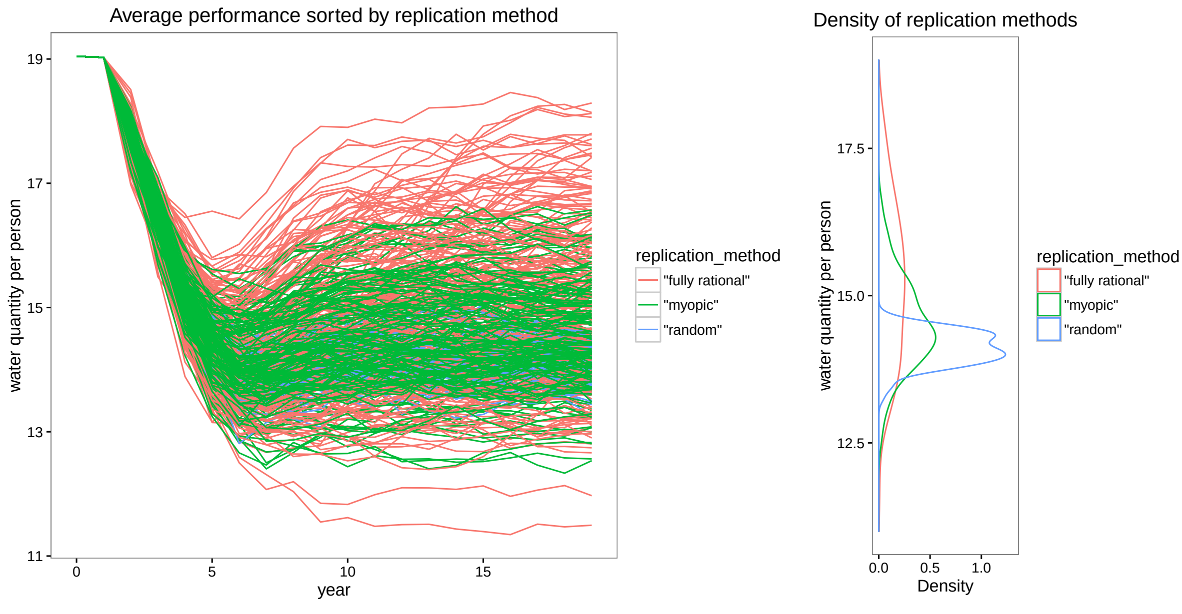
In this section the general behaviour of the ABM is described. We have seen an interesting model behaviour, where the average performance of the districts shows a steep decline, recovers slightly and then stabilises for a long period of time. In the quest to verify to what extent the behaviour is an artefact of the way the ABM is encoded we have seen that probably both the level of stabilisation and the initial conditions are not completely correct. This does not hinder the purpose of this thesis, as we do not try to predict the future state of rural water supply in Uganda. Furthermore, we have seen that the behaviour of the average performance of the districts is triggered by the functionality percentage of the water infrastructure. We argued that on the one hand this is a model artefact, as the implementation of assumptions led to insufficient budget to remain at the level of the initial conditions, and on the other hand the results indicate a non-effective policy for budget allocation. In addition to this there can also be a source of money in the real system that is not represented in the model. The discussion about the general model behaviour cleared the path to analyse the scenarios for replication and variation from the experimental set-up in chapter 6, as we should extract the information given all the considerations described in this section.

7.2 Analysis of Scenarios for Replication and Variation

Up to this point we have seen the average performance of the districts in the experiment. The behaviour of the model is explained in the previous section. In this section the analyses of the scenarios for replication and variation are described. We first go into the replication methods, next we turn to the variation methods, in order to then return to the five possible scenarios for interactions between replication and variation methods.

What would happen with the general system behaviour under different methods for replication? We have seen that all simulation runs follow a similar drop. We also have seen that the level at which the simulations become stable is spread over quite a range. A fair suggestion is that the replication method has influence on the level at which the performance stabilises. Let's revisit the meaning of the different methods for replication. There are three methods: random, myopic and fully rational. They all represent a structure of learning that is observed in the rural water system in Uganda. The *fully rational* method represents a learning structure at national scale, where a good or an effective policy from one district is picked up by the TSU, communicated to the MWE and consequently communicated to all other districts in the form of a law or undertaking. The *myopic* method represents learning structures at a regional scale, where districts learn from each other about the effectiveness of policies at regional learning venues, such as learning fora or WASH alliances. The *random* method represents a structure of learning between districts, where one district communicates with one other district. The methods thus all represent a learning structure at a different scale. An extensive description of these learning structures was provided in section 3.3 in Figure 3.2.

The hypothesis is that the fully rational learning structure is resulting in better performance, as policies are spread over a larger scale. However, this also means that a bad policy can be spread quickly. The policy we are looking at is the allocation ratio. An allocation ratio that in theory is not optimal can in practice be considered very good, for instance when the initial conditions of that district with that specific ratio were very good. A bad policy might then be spread to many districts. The hypothesis is therefore that even though the average performance of the fully rational method is best of the three methods, it might also cause some of the worst runs. The random replication method is assumed to perform worst or the three methods, as the learning processes are at a low scale and districts choose a district at random. The myopic method is assumed to perform somewhere in between the two. Expected is that in the myopic method the spread of outcomes is less than in the fully rational method as the communication is limited to the boundaries of the region. Average performance of the system under the condition of a myopic replication method, therefore, is assumed to be more in balance. The outcomes of the different replication methods is visualised in Figure 7.5a



(a) Performance coloured by replication method

(b) Density of runs after 20 years

Figure 7.5. Average performance delineated by different methods for replication. The left shows all runs, coloured by the various replication methods as shown in the legend. The right shows the density of the runs that end at a certain water quantity level after 20 years.

In the figure we see the simulation runs again, but this time coloured. The runs are coloured according to the replication method that is used in the run: red for the fully rational method, green for the myopic method and blue for the random method. What we see is that there is a concentration of myopic runs in the centre of the range. The random method can hardly be seen in the visualisation. At the top and a few runs at the bottom, the extremes, we see some simulation runs with the fully rational method. As the output of the simulation runs overlap each other, we need a second figure to support this one. In Figure 7.5b a density plot is shown. The plot is a continuous function that is fitted on the end values of the simulation runs. In other words, all simulations end up at a certain water quantity level. If more runs end up at the same level, the density plot shows a larger deflection of the y-axis.

The combinations of the graphs confirm some of our hypotheses. First of all, the fully rational method seems to result on average in a higher national average water quantity of the districts. The fully rational method furthermore, also shows some really bad outcomes. The myopic replication method is similar to the fully rational method, but the effects are less big. This is caused by the fact that policies are spread over a smaller area. In a single simulation, certain regions can spread a very bad ratio and other a really good one and the effect will be average, whereas in the fully rational method these effects might be more influential. The random method shows some interesting behaviour. In the second plot, we can see a very stable behaviour of the simulations runs with a random method. None of them perform really well, relatively, and none perform really bad. All runs end between a level of 13 and 15.

In order to support any more claims another figure is drawn. At this point we see the behaviour of all simulation runs, but as many are plotted on top of each other we needed the density plot. In the density plot, however, we miss some statistical information that we can use to support the argument in favour or against our hypotheses. Therefore Figure 7.6 shows a box plot of Figure 7.5b.

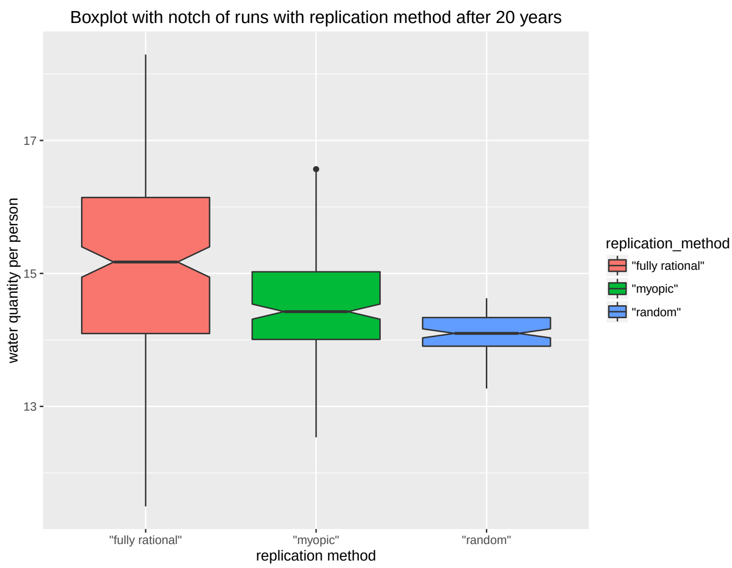


Figure 7.6. A notched box plot of replication methods

In the box plot we see another visualisation of where all simulation runs end up, i.e. the level at which the runs stabilised. Coloured by the replication method used in a similar way as coloured before. Before analysing the figure and providing any arguments in relation to the hypotheses I have to explain the *notch* in the box plot. As the caption says the figure shows notched box plots. A notched box plot is slightly different than a normal box plot. The notch in the box plot shows the 95% confidence interval of the median of the box plot. This information allows to draw conclusions about the significance of the difference between the runs with a different replication method. In the case that the 95% confidence intervals of the median of the output of the simulations with different replication methods do not coincide, we can say that there is a significant difference between the output of the runs [Mcgill et al., 1978]. A supporting visualisation of the notch is shown in Figure 7.7.

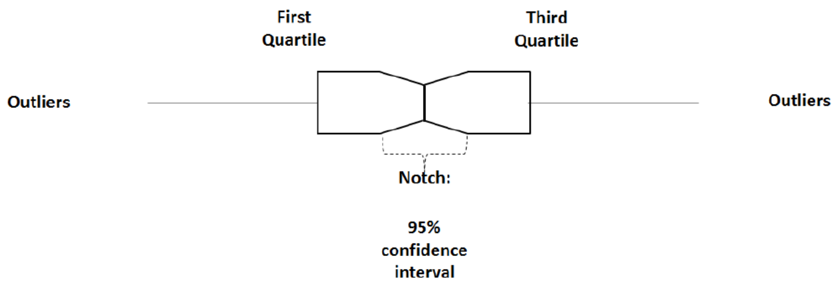
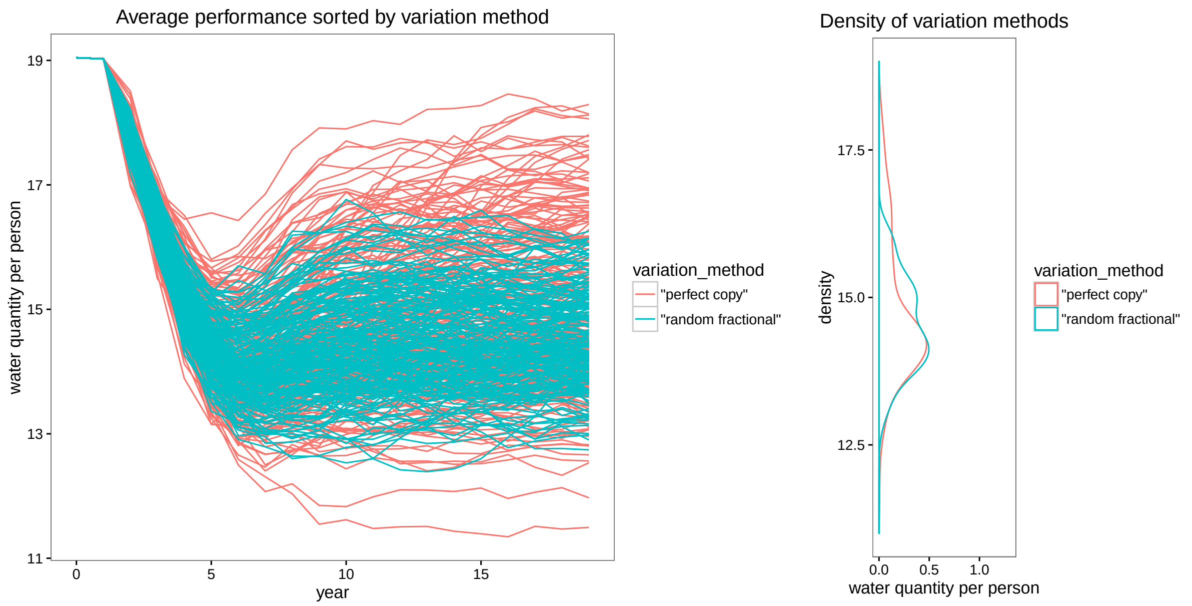


Figure 7.7. Basic visualisation of a notched box plot, adapted from Slangen [2016], based on Mcgill et al. [1978]

Back to the analysis of the replication method. In the notched box plot most of our hypotheses are confirmed and some interesting conclusions can be drawn. The fully rational replication method performs significantly better than the myopic method which in turn is significantly better than the random method. We can conclude this as the 95% confidence intervals of the median of the plots do not coincide with each other. A second observation is that the spread of the outliers is large in the fully rational method (water quantity between 12 and 18) and declines the smaller the scale of communication in the learning structure that is represented (between 13 and 17 for the myopic method and between 14 and 15 for the random method). The hypothesis of a larger spread is therefore confirmed. The outliers in the fully rational method are caused by the fact that the ABM is sensitive to initial conditions, i.e. a district that performs well and has a very good allocation ratio (e.g. zero unspent budget) is spread over at least half of the districts in one year time. This allocation ratio is then likely to survive over time, as also the best district keeps on performing well with a good ratio. The initial allocation ratio of the districts is determined on a stochastic basis, this mean that the ratio is randomly chosen within the set boundaries for CapEx and CapManEx for every district in every simulation. The effect of a good or bad initial condition is limited to a region in the myopic method and has almost no effect in the random replication method, hence, the spread of the outliers declines.

What does this all mean in practice? First of all, remember the assumption that every district here is willing to learn. In practice many districts just do what they did yesterday [Nabunnya et al., 2016]. The replication methods represent different learning structures at different scales. In practice they are used in parallel and on different time scales. Image that the national learning structures take up more time than the regional and that the inter-district learning structures is used more often than the quarterly or monthly regional learning venues. What we can see by means of the simulations with the ABM is what the learning structures in an isolated way would result in. At this point policy makers in Uganda should discuss their goals regarding national policies on rural water supply. These figures support the considerations: if you aim for more stable performance, make sure districts randomly meet each other and learn from each other. If you aim for radical improvements via the national learning structure, be aware that the consequences are greater and that they can turn out negative as well.

We turn our attention from the replication method to the different methods for the variation process. There are two options for the variation method: in the first method the districts make perfect copies of their replicated ratio and in the second method the districts slightly adjust the selected ratio. Regarding the latter we described that this represents two things: the unconscious *mistake* in copying a ratio and the conscious process of adjusting the replicated ratio to the own situation. The hypothesis is that the *perfect copy* method results in more extreme behaviour, as extreme allocation ratios are blankly imitated. The *random fractional* method is expected to result in more moderate system behaviour, as variation is added to those extreme allocation ratios. The variation method is therefore very closely connected to the results of the replication method, as the scale of communication of ratios is determined in the replication process. I expect the variation process to mainly contain the effect of the replication processes. After the standalone analysis of the variation method we get to the analysis of the scenarios of the experiment, where replication and variation methods are combined. In Figure 7.8 the same two graphs as in the replication experiments are shown: one showing the average district performance over time coloured by the variation method and one showing the density of outcomes of the simulations after 20 years, again coloured by the variation method.



(a) Performance coloured by variation method

(b) Density of runs after 20 years

Figure 7.8. Average performance delineated by different methods for variation. The left shows all runs, coloured by the various variation methods as shown in the legend. The right shows the density of the runs that end at a certain water quantity level at the end of the simulation.

What we see in the left figure confirms some of our hypotheses. Both the extremely good runs and the extremely bad runs are induced under the perfect copy method. The runs for the random fractional method seems to perform more moderate. If we look at the right figure, however, the conclusion is more difficult. The two density plots do not seem to avoid each other that much. They are close together below a water quantity level of 12.5. Then at a level of 15, they diverge a bit, more random fractional runs end up at that level and it seems that these runs are spread over the higher levels in the perfect copy method. Some support of the analysis is given by the notched box plots in Figure 7.9.

What we can see in the figure is that the median of the two runs are similar. This means the runs on average perform the same and there is no significant difference between the two methods. Second, the outliers of the perfect copy method are spread over a much larger range than the random fractional method: 12-18 compared to 13-16. This could mean that as districts adapt a policy they selected to imitate, there are less extreme situations. A third concept to notice in the figure is the spread between

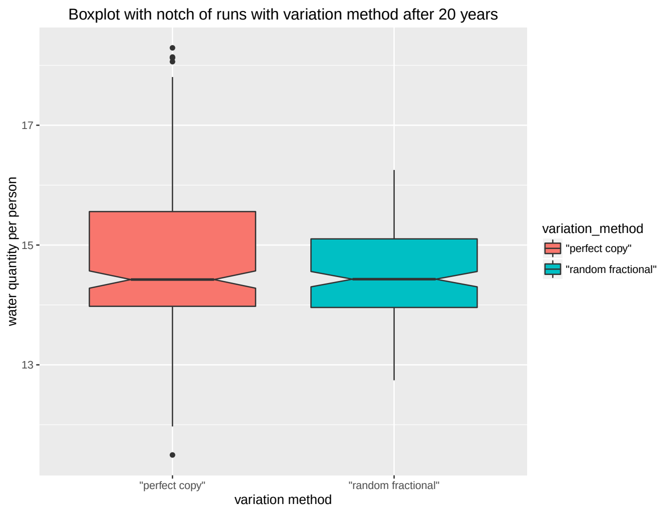


Figure 7.9. A notched box plot of variation methods

the median and the 75 percentile in the perfect copy method. It shows that many simulations end up at these levels.

Reflecting on the insights here I would argue that the random fractional variation method performs better than the perfect copy method. The median is the same, but the spread is less, resulting in a more moderate performance. For this moment we conclude that the perfect copy method strengthens the conclusions about the replication method. The random fractional method reduces the effects induced by the different replication methods.

Up to this point we have seen the isolated working and effects of the replication and variation methods on the average system behaviour. The experiment is designed to see the effect of the scenarios that combine the scenarios for replication and variation. The isolated analysis resulted in many important insights that we hope to see confirmed by the analysis of the different scenarios. The output of the ABM for the different scenarios is visualised in Figure 7.10.

The figure shows five scenarios. Each of the scenarios is represented by a box plot that shows the average behaviour under the conditions for replication and variation as specified in the scenario over a period of 20 years. The difference between the left and the right graph is the variation method: either the perfect copy method or the random fractional method. From top to bottom the difference is the replication method: either fully rational, myopic or random. In the first scenario we observe both the biggest range of endpoints of the simulation as the highest median. The fully rational perfect copy scenarios differs from the random fractional counterpart in the sense that the range of the simulation runs is lower and the median performance is lower: 15 compared to 16.5 in the perfect copy run. In the myopic method we can draw similar conclusions. First of all the median of the perfect copy myopic scenario is higher that its random fractional counterpart. The difference is very little though: 14.5 compared to 14. Second, the spread of the perfect copy scenario is bigger, induced by the model sensitivity to initial conditions, similar to the fully rational perfect copy scenario. In the random replication method we see our previous conclusions confirmed. The spread is lowest and the median is lowest of the five scenarios.

In this section we have seen a standalone analysis of the difference in methods for replication and for variation, as well as a combined analysis represented by the five scenarios. The various scenarios for

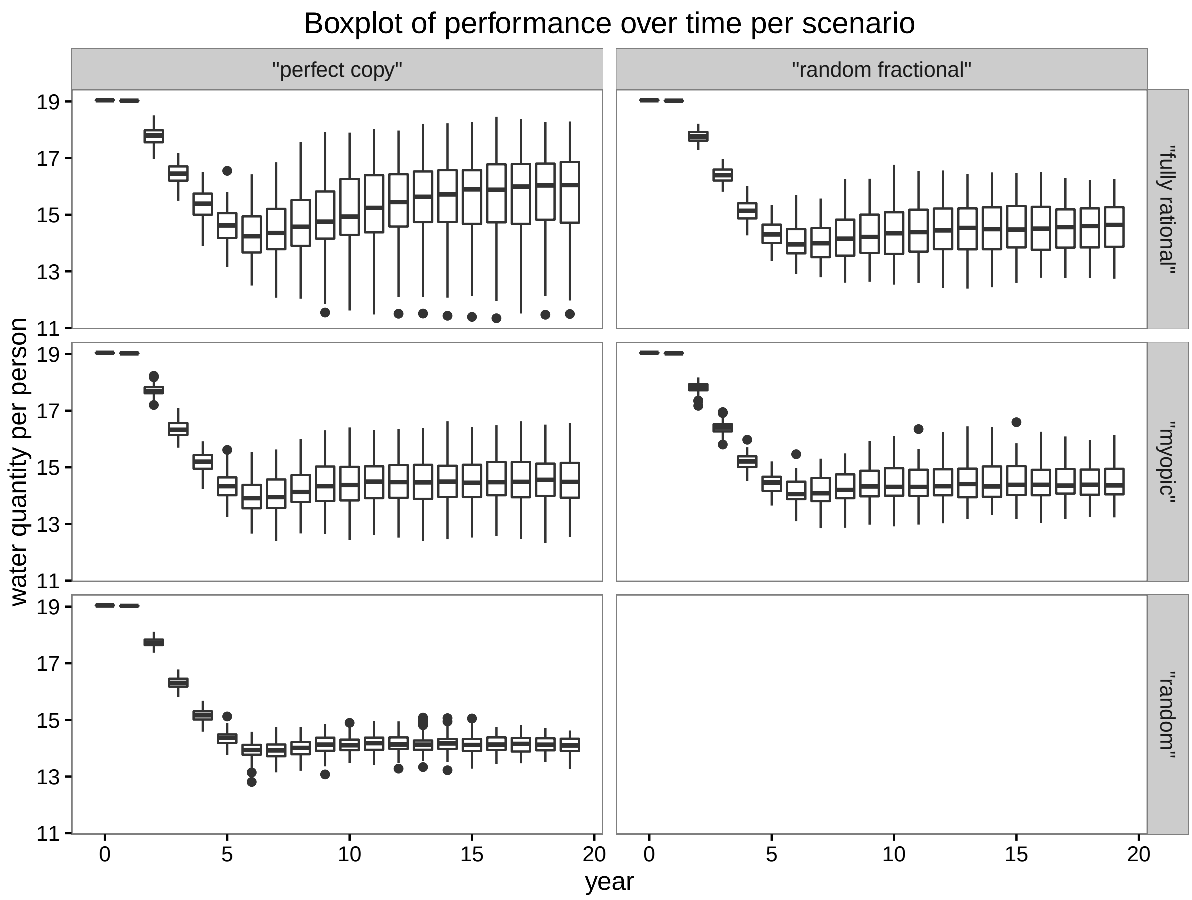


Figure 7.10. Results of the experiment. All simulation runs are separated to their methods for replication and variation.

replication allow for Ugandan policy makers to see the isolated effects of the three learning structures. The next step for the policy makers is to consider the goals of national policy regarding rural water supply and to make more educated decisions on the learning structures based on the output generated in this modelling study. An outcome of such a decision can be to support certain learning structures more than others or to reconsider the time scale at which the structures are used. Another insight for policy makers in Uganda is to reconsider if the current institutional set-up allows these learning structures well enough in every region of the country. Regarding the different methods for the variation process we have seen that the interpretation very much occurs in the context of the replication method. The implementation of the variation method make that the methods either support the extremes of the replication method (perfect copy) or contain the effect (random fractional). The question whether it is better or worse to adapt a policy is difficult to answer. On the one hand we see that in the random fractional method the addition of variation to the policy ensures that changes in policy are not radical, as they on average stay closer to the current policy of the districts. On the other hand, we would expect that the conscious adjustment of a policy should result in better performance on average, but we don't see that reflected in the model outcomes.

7.3 Loosened Conditions for the Allocation Ratio

The focus in this section is on the allocation ratio. The allocation ratio is the policy of interest in the ABM and in the implementation of the policy is the subject of the communication between the districts. In this section first a small verification test is done to see if the districts actually learn how to best implement the allocation ratio. Second, an analysis of the current implementation of the policy set by the MWE at national level is given. The analysis is induced by the findings in section 7.1 and is further analysed in this section.

We want to verify whether the districts in the simulation learn how they can best implement the allocation ratio. We also want to verify whether an allocation ratio that is considered good actually results in better performance. For this consideration to be made, we need to understand what a *good* allocation ratio is. The implementation of the allocation ratio allows us to argument for good and bad allocation ratios. The allocation ratio consists of three ratios for a certain expenditure: ratio for CapEx, ratio for CapManEx and a ratio for unspent budget. A visualisation of the boundaries set by the MWE in the current implementation of the allocation ratio is shown again for convenience in Table 7.1.

	Definition	**Short**	**Boundaries (% of DCG)**
X	Capital Expenditure	CapEx	70 - 100
Y	Capital Maintenance Expenditure	CapManEx	0 - 13
Z	Unspent Budget	Unspent	0 - 30 (100 - X - Y)

Table 7.1. Conceptualisation of the District Conditional Grant

Starting with the ratio for unspent budget, the hypothesis is that a ratio that results in good performance of a district has a low ratio for unspent budget. Unspent budget is returned to national level and therefore a districts invests less than possible in their water infrastructure. The optimal ratio for unspent budget would therefore be 0. This means that the ratio is completely used by CapEx and CapManEx. For the ratio for CapManEx we can reason that a higher ratio is probably more beneficial for the water service levels in the long term. This argument is supported by the findings in the first section of this chapter that indicate that there is not enough budget available for the district to repair non-functional infrastructure. A repair of a broken water point is cheaper than investment in a new water point, hence the hypothesis is that a higher ratio for CapManEx results in a higher average water service level. The maximum allowance for CapManEx budget is 13% of the total budget and therefore I argue for an optimum of 0.13. For the ratio for CapEx budget in this case it holds to say that it is a result of the ratio for CapManEx and the ratio for Unspent budget. Therefore the hypothesis is that the best behaviour of the system is approximately with a ratio for CapEx of 0.87. The optimal ratio in the ABM therefore is [0.87 : 0.13 : 0]. Be aware that this is an artificial optimum and not an optimum in practice. Under the conditions in the ABM and the assumptions that were needed to implement the allocation ratio this is the optimal allocation ratio.

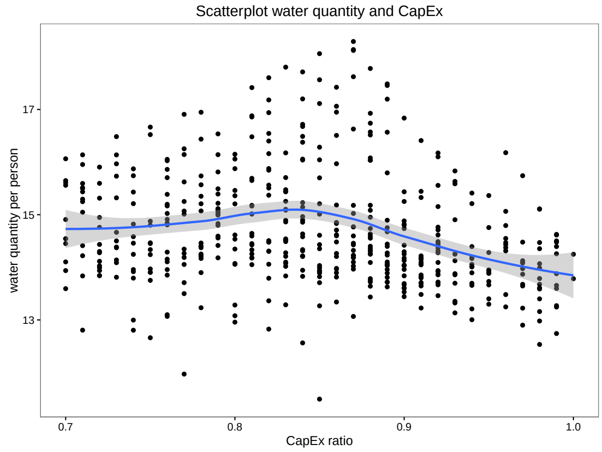
We would expect that districts through communication about the allocation ratio they implement gradually learn to use the allocation ratio in the best possible way. A good allocation ratio is furthermore assumed to result in the highest district performance measured in water quantity. There are some caveats, for instance that the districts have different starting positions and therefore it is difficult to see whether they indeed learned the best allocation ratio, rather than a ratio, whether it is good or bad, of a district with good starting conditions. However, the hypothesis is that the districts on average will learn what the best allocation ratio to use is. The figures that supports the analysis are shown in Figure 7.11.

In the three figures we see a scatter plot. Represented on the x-axis is the allocation ratio for either CapEx, CapManEx or Unspent of the district that performed best in the national ranking after 20 years. Represented on the y-axis we see the average water quantity delivered by the 110 districts. Every point in the simulation therefore shows the output of a single simulation - it shows what level the average performance of the system reached, and the corresponding ratio of the best performing district amongst them. Second, we see a line drawn through the scatter plot and a shady area near that line. The line is a regression line, fitted with a generalised additive model. The regression line is fitted to the data points by combining additive models with generalised linear models. The shady area around the line shows the 95% confidence interval of the regression line.

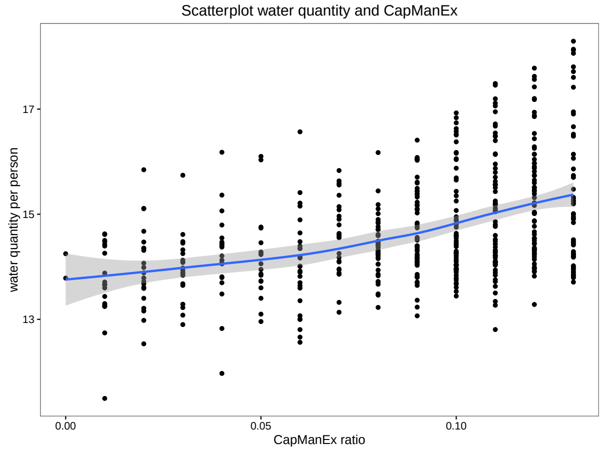
Starting with the ratio for CapEx in Figure 7.11a the regression shows an optimum around a CapEx ratio of 0.85. The highest outliers are around 0.87, the artificial optimum of the ratio. Regarding the density we do not see much difference on a first glance. In Figure 7.11b we see the CapManEx ratio. Two things are interesting: one, the regression line shows an upward trend, stopping at 0.13, the boundary of the allowance for CapManEx in the ratio. Two, there are more data points the higher the ratio gets. This could indicate that districts on average indeed learn that it is better to spend more budget on CapManEx. The hypothesis of learning can best be seen at the visualisation of the unspent scenario in Figure 7.11c. The regression line shows an optimum around 0.08. This does not tell us much. However, we see that the highest outputs are higher the lower the unspent ratio. Second we see that the density of data points is denser at at 0, but not necessarily higher. Third, we see that almost no runs end up spending more than 20% on unspent budget, which indicates that districts learn to spend the money in a sane way.

What this means is that we see some hints that the districts learn, as they show progress towards the artificial optimum of the allocation ratio. But we also can conclude that this is not too obvious from the results. A possible explanation again is that it is not clear which districts are responsible for spreading and having the best allocation ratio. It is possible that it is just a district with *lucky* starting conditions, i.e. a relatively high DCG budget, performs significantly better in every run. This could mean that it doesn't matter what ratio the district uses, it will end up high anyway. Furthermore, these results indicate that the hypothesis that is raised in section 7.1 is plausible. In the graph of the CapManEx ratio we observe a trend that is clearly upward: a higher ratio for CapManEx of the best performing district means that those districts on average perform better. What would happen if districts could actually spend more budget on CapManEx?

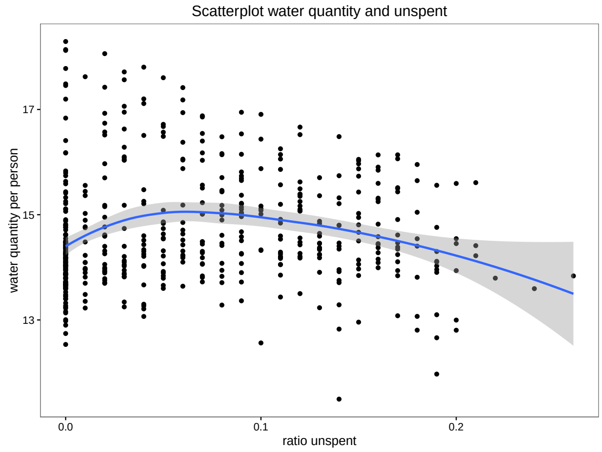
We continue to an analysis where the districts are free to allocate the budget they receive from national level. The restrictions - maximum 13% on CapManEx and minimum 70% CapEx - are excluded from the simulations with the ABM. The hypothesis is that the average performance of the district will be higher compared to the simulation with the restrictions for budget allocation. This hypothesis comes from the steep decline immediately after the start of the simulations that we have observed in the general model behaviour in section 7.1 and the corresponding conclusion that this is fed by a drop in functionality percentage of the water infrastructure in the districts. This could mean that the districts do not have enough budget to maintain the infrastructure given the rate of the failure of the infrastructure. This



(a) Ratio for CapEx at t=20 and corresponding water quantity



(b) Ratio for CapManEx at t=20 and corresponding water quantity



(c) Ratio for unspent at t=20 and corresponding water quantity

Figure 7.11. These figures show the relation between the allocation ratio of the best performing district in the nation and the average performance of the system in terms of water service levels. A regression line is plotted to show the fitted relationship. The shaded area shows the 95% confidence interval.

would plead for an increase in budget for CapManEx. The plausibility of this hypothesis is increased in this section by the upward trend in the regression line in Figure 7.11b. An experiment is set-up in the ABM to run without the restrictions on the allocation ratio. A 100 simulations are performed - 20 simulations for each of the scenarios for replication and variation to have a similar representation as in the original experiment - over a time span of 20 years. In the simulations the minimum ratio for CapEx is varied between 0.7 (restrictions by MWE) and 0 (representing no restrictions). The maximum ratio for CapManEx is varied between 0.13 (restrictions by MWE) and 1 (representing no restrictions). The output is visualised in Figure 7.12.

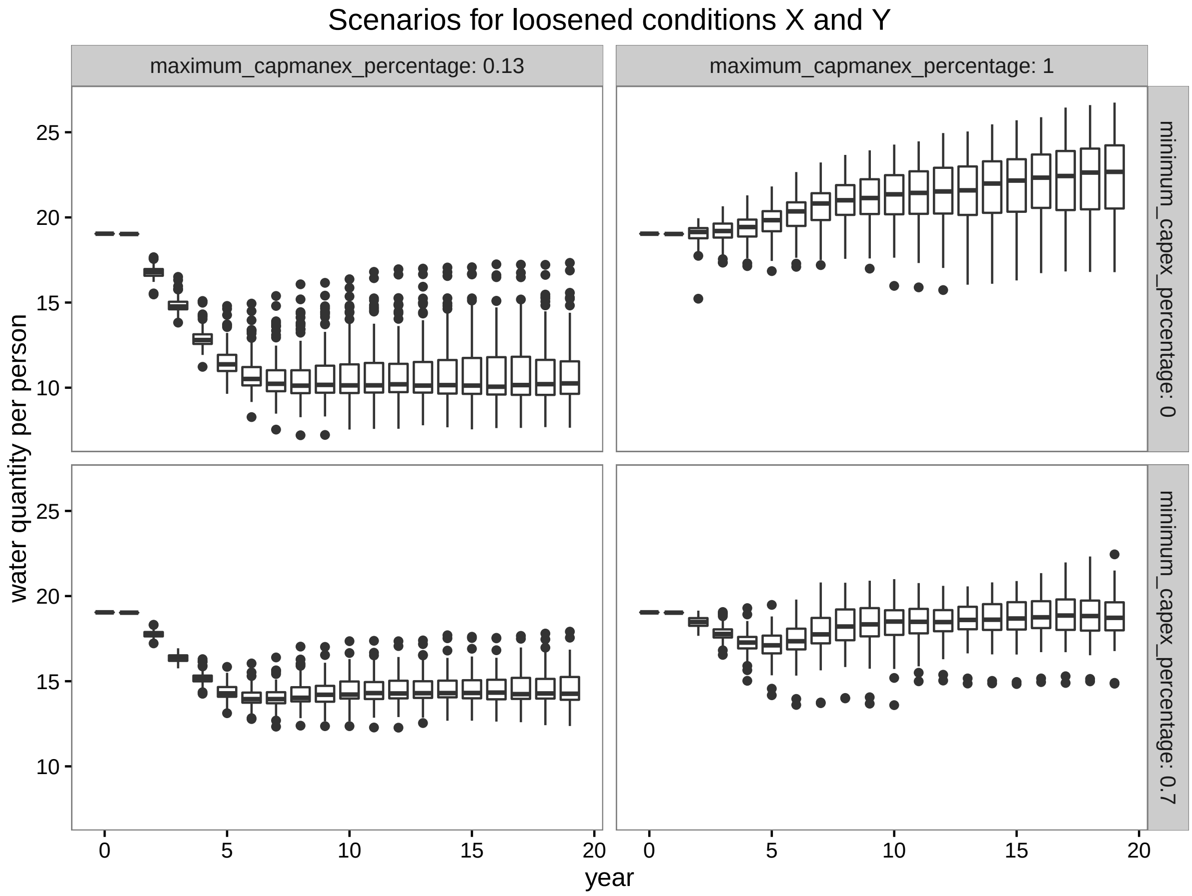
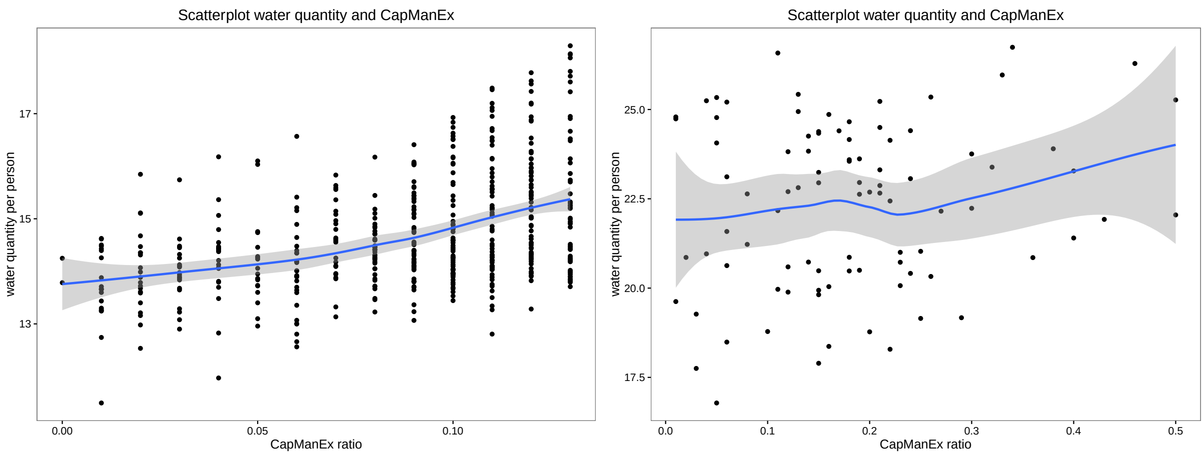


Figure 7.12. Loosened conditions for allocation ratio. Runs for the default conditions for the allocation ratio and the loosened conditions in a matrix. Left-Right: difference in maximum CapManEx ratio - either 0.13 (restricted) or 1 (unrestricted). Up-down: difference in minimum CapEx - either 0 (unrestricted) or 0.7 (restricted).

In the figure we see four separate box plots over a period of 20 years. The plots represent the different settings for the ratio of CapEx and the ratio of CapManEx, plotted against each other. The boxes show the statistics of 25 simulations - a fourth of total of 100 - plotted over time with their particular settings for CapEx and CapManEx. The difference between left and right is the maximum ratio for CapManEx - either 0.13 (left) or 1 (right). The difference between top and bottom is the minimum ratio for CapEx - either 0 (top) or 0.7 (bottom). The comparison of two scenarios is of particular interest. The plot at the left bottom of the figure represents the situation as we have seen it in all previous analyses: ratio for CapEx restricted with a minimum of 0.7 and ratio for CapManEx capped at 0.13. The plot at the right top of the figure represents the situation were all restrictions are absent: a minimum of 0 for the

CapEx ratio and a maximum of 1 for the CapManEx ratio. What we see in the *restricted* scenario is the familiar drop of the average water quantity delivered by the districts and next the stabilisation. There is a major difference in the *unrestricted* scenario. The behaviour does not show a drop, instead the average performance slowly rises and continues to rise over time. Even the most negative outliers stay around a water quantity of 20, where the median grows to approximately 24 in 20 years time. Could this mean that the budget in the current implementation of the policy by the MWE is indeed ineffective?

To understand if this is true first a verification is performed to see if the districts actually spent more budget on CapManEx in the *unrestricted* simulation runs. For this purpose another scatter plot is constructed. The hypothesis is that the ratio for CapManEx exceeds the ratio of 0.13. In Figure 7.13 the CapManEx ratio of the restricted run is shown (left) besides the CapManEx ratio of the unrestricted run.



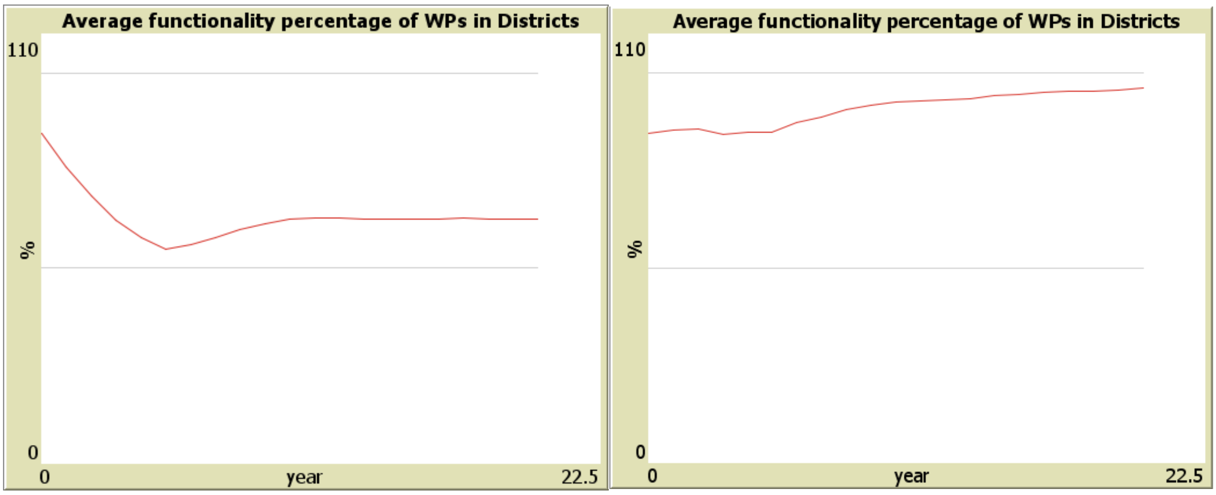
(a) CapManEx ratio in restricted simulations **(b)** CapManEx ratio in unrestricted simulations

Figure 7.13. This figure provides evidence of the trend between the ratio of CapManEx of the best performing district and the national average performance. It shows the relation between the allocation ratio of the best performing district in the nation and the average performance of the districts. A regression line is plotted to show the fitted relationship. The shaded area shows the 95% confidence interval.

What we see in the figure is that the unrestricted runs perform much higher than the restricted runs. There are less data points in the unrestricted run as fewer simulations are done, as can also be observed in the shady area surrounding the regression line. The trend and more important the difference between the experiments, however, already is clear with this amount of runs. We can see that the best performing district spent up to 50% on CapManEx. Concluding that the policy of the MWE is ineffective, however is too early. Consider for instance the fact that there is no geographical representation in the ABM of the spread of the water infrastructure within the districts. The national government follows the vision to firstly provide every single person in rural Uganda with sufficient water and thereafter, I assume, raise the service levels for everyone. This connects to the fact that the performance indicator in the ABM - water quantity - is a different performance indicator than used by national government - coverage. We encountered this discussion before, in the conceptualisation of the ABM. Does this mean that the outcomes of the unrestricted experiments result in much water for a few and too little water for many?

It seems to be a very fair point that if you design your policy to ensure everyone has water, you focus on investments in new infrastructure. This ensures that new water points are built for the rural communities that still experience insufficient water service levels. However, the body of evidence in this thesis grows to state that the current implementation of the policy results in ineffective allocation of available financial resources. The unrestricted simulations show that with the same amount of budget, the average performance of the districts is raised to a median of 24 after 20 years, compared to a median of 15 in the restricted variant. This is quite a difference. The only caveat from the perspective of the vision of the current policy is that it might not serve everyone. The following contradicts this.

I perform two single simulations in the ABM environment: one with restrictions on the allocation ratio and one run without restrictions. First, the average functionality of the water infrastructure is analysed. We expect that the functionality in the unrestricted runs is much higher, as the amount of budget for investments in maintenance grew, as we have seen in Figure 7.13b. The average functionality of the districts in the two runs is shown in Figure 7.14.



(a) Average functionality in restricted simulation **(b)** Average functionality in unrestricted simulation

Figure 7.14. Difference between a run with restrictions on the allocation ratio and a run without restrictions. Measured in average functionality of water infrastructure in the districts. The red line shows the average performance. The grew lines represent the y-values 100 and 50 to support interpretation of the figure.

In the figure we see two graphs. A similar figure to the figure on the left we have seen before in the beginning of this chapter. It was used to prove that the functionality percentage of the infrastructure is key to understand the behaviour of the average performance of the districts. It also raised the hypothesis that there is not enough budget for CapManEx available for the districts. The figure on the right shows the simulation without restrictions on the allocation ratio. We see that the average percentage of functional water infrastructure grows in a similar way as the average performance of the districts. This is also what we expected. However, this still leaves us with the trade-off between serving everyone a little and serving some a lot. Up to this point we don't know which of the two the simulations represent. Therefore we perform another analysis. The analysis consists of the same two runs as are represented in Figure 7.14. The analysis is simple: count the functional and non-functional water points after 20 years for both simulations. The result is shown in Table 7.2.

Factor (measured at t=20)	Restricted run	Unrestricted run
Operational water points	107.860	183.109
Non-operational water points	63.500	4.500
Total number of water points	171.360	187.609
Functionality percentage	63%	96%
Average water quantity	14,5	24

Table 7.2. Water point data of two simulation - one restricted run and one unrestricted run, measured after 20 years

These results are remarkable. Though it is just one simulation it shows that not only the average performance of the districts and the average functionality of the water infrastructure are better in the unrestricted simulation, but also that the unrestricted simulation results in more water points. The percentage of non-operational infrastructure is much lower, the total number of water points is 10% higher and the amount of operational water points is 80% higher in the unrestricted scenario compared to the restricted scenario. With this knowledge the importance of the assumption that water points that are non-operational for a period of five years are considered abandoned grows in importance. I assume that the number of water points that are built in the restricted simulation is higher, but that many water point are never repaired and are considered abandoned after a period of five years - in terms of the ABM this means the WP-agent dies and is removed from the simulation. In the unrestricted run I suspect that less water points are built in total, but that all water points are repaired before they are considered abandoned. This results in much higher water service levels. Now considering the caveat that different performance indicators are discussed, we see that there are more water points in the unrestricted simulation. Without considering the exact location of the water points, we can assume that they are spread over a larger area and therefore the coverage numbers are also higher in the unrestricted scenario and that would mean that more people reached with an unrestricted policy.

The analysis in this section could mean the following: the current implementation of the policy about the allocation ratio leads to ineffective use of resources. The current focus on building new infrastructure results in many new water points, and also leads to insufficient budget for maintaining the existing infrastructure and the newly constructed infrastructure. A more effective resource allocation would be to ensure enough budget for maintaining all current infrastructure and gradually expand through investments in new infrastructure. In this way current and new infrastructure remains operational.

8 | Model Validation and Expert Reflection

With the results of the experiment and the findings about the allocation ratio in mind I took this thesis to a number of experts to discuss and reflect on the insights generated with the ABM. The critical assumptions in the ABM are revisited as well. In the conceptualisation phase of the research I consulted with experts to form the right hypothesis about the implementation of learning in rural Uganda, through regular meetings with sector experts and an interview with a panel of people that work in the WASH sector in Uganda. This method is called *companion modelling* [Dam et al., 2013]. In constant consultation with various experts at Delft University of Technology and IRC I developed the conceptualisation of the system and the conceptualisation of learning, including the assumptions needed in the various abstractions of the conceptualisation. Some of the same experts are visited again to discuss the insights generated with the ABM, some new experts are consulted to discuss both the assumptions and the model insights. In Table 8.1 an overview of the interviewees is shown. A summary of each of the interviews is presented in appendix C.

#	Expert	Expertise
1.	Abby Onencan	PhD candidate Sustainable Nile River Basin Management, Faculty of Technology, Policy and Management. Delft University of Technology
2.	Patrick Moriarty	Chief Executive Officer, IRC
3.	Martin Watsisi	Regional WASH Advisor IRC Uganda
4.	Yared Abebe	PhD candidate Urban Water Systems, UNESCO-IHE, Delft

Table 8.1. Overview of Expert Interviews

In section 8.1 we revisit the critical model assumptions. This serves as a validation step. The question that the experts is asked is if the model assumptions reflect what they observe in the actual system. In the interviews we systematically went through the list of assumptions. The section provides a summary of the discussions with the experts. In the section I provide a factual validation of the model assumptions, thereby allowing some reflective comments of the experts. An extensive reflection on the implications of the model assumptions is provided in the next chapter. This step is performed, because the representation of the system in the ABM is many steps away from the actual system. Even though the assumptions are created in consultation with expert through companion modelling, we revisit the assumptions with the same and with different experts. The assumptions that we use to create the representation of the system form the model behaviour, steer the results and thereby influence the conclusions that we are able to deduct from the study. In comparison to the verification in section 5.3, where I show why one should trust this particular implementation of the conceptual model into the ABM, in this section I show to what extent the ABM accurately represents the real system and that we can therefore trust the conclusions that are based on the insights generated with the ABM.

Second, in section 8.2, we assess, discuss and reflect on the behaviour generated in the ABM. This section serves as a reflection on the model behaviour and assesses the insights that we can generate with the model behaviour. The question that the experts is asked is what the model results could mean if we try to translate the model results to patterns we observe in the real system. In the interviews three parts of the model behaviour is analysed. The first part concerns the general model behaviour, for instance providing a reflection of the experts what could cause the steep drop and level of stabilisation. The second part is about the scenarios for replication and variation and the third part considers the insights generated about the restrictions in the policy for the allocation ratio. These parts coincide with the sections in chapter 7.

8.1 Validation of Critical Model Assumptions

In this part, focal points from the discussions about the model assumptions with the various experts are described. The discussion points are summarised to points about multi-level governance, the representation of a district, the water infrastructure, the District Conditional Grant (DCG) and the processes of selection, replication and variation.

Multi-level Governance: In consultation with the experts, firstly, some remarks and caveats are made about the institutional organisation in Uganda. The overarching remark is that the system in Uganda is *messy*. Although there is a formally defined hierarchy in the sector, in the form of the District Implementation Manual [Ministry of Water and Environment, 2013b], processes and structures in the sector are often different and more ambiguous than described. Firstly, an expert mentions that the lines of communication in the sector between district level, regional level and national level are varying per district and in terms of time. In practice communication lines work more along the line of who knows who in Uganda.

Next, even though the sector is decentralised, most of the information spread is top-down. When a system is decentralised, you need to realise there is a need for strong information systems and capacity to build and support them at different institutional levels. Uganda is in the process of realising such strong information systems. The consequence is that much information is spread top-down through the sector, rather than bottom-up from the communities to the districts to the national level. This means that the interpretation of the model outcomes should reflect on stable communication lines: *if the communication lines were as we assumed in the ABM, we can draw these and these conclusions...* It furthermore allows to draw conclusions about the communication lines themselves. We for instance see that the national learning structure can provide a high median water quantity, based on this we can advise to build the capacity of this learning structure to function properly.

Second, an expert remarks that the regional level in Uganda is not a *solid* or *tangible* level. Regions are messy. The regional level is questionable in terms of authority. Furthermore, there are many different interpretations of regions. A district can belong to several regions, depending on the demarcation that you choose. Part of the discussion in Uganda is on what basis regions should be demarcated, this can be according to current institutions, such as the learning fora where districts meet, and demarcation can be according to river basins which makes more sense in terms of water resource allocation. The ABM assumes a stable regional level with sufficient authority to foster regional learning venues. The results in the ABM indicate that policy makers in Uganda should consider to strengthen the regional level in the way it is assumed to function in this thesis.

The third remark of an expert about the multi-level governance situation in Uganda concerns the role that the institutional levels fulfil in practice. The expert explicitly mentions that the institutional levels all enact a different role in the decision-making related to rural water supply. The national level, containing the ministries, enacts as a regulator of the sector. The regional level, subsequently, is often seen as an intermediate. The Technical Support Unit is a good example, because they communicate with both the district level and the national level. The district level serves as service authority, responsible for delivering water services to the rural population.

Representation of a District In the interviews a number of discussions were about the representation of the districts in the ABM. Firstly, districts in Uganda are not only different in terms of geographical aspects, such as elevation and natural resources, but also in terms of organisation. Districts organise and operate in different ways and this is not represented in the model. Districts can for instance have different goals, e.g. optimising and earning money from the water supply system versus a conservative approach, where the district authorities try to serve everyone in the district. In the model the districts are simple, unambiguous agents who all follow the same set of decision-rules.

Connected to this remark is a remark from another expert, who explains how the District Local Government is a service authority and how it uses service providers to implement water supply projects. Examples of service providers are contractors and hand pump mechanics. The availability and level of the service providers differs from district to district and even within districts. The dynamics that are caused by the interactions between the service providers and the service authority is not part of the ABM.

In reflection on the assumption of equal topography in the districts one of the experts mentions it is a fair assumption. The only factor that is left out is the different possibilities for water infrastructure. In discussion of how this could have been represented we argued for a case of limited resources for some districts where implementation in practice is more difficult. A second interesting remark from another interview makes a connection between the assumption of topography and the assumption of the budget the districts yearly receive. In the budget of the District Conditional Grant, the national government accounts for the topography in a district: districts with heavy terrain receive more budget than districts with an easy terrain. The districts in the ABM, however, are considered equal, but they receive the budget that is based on the actual budgets the districts receive that includes the consideration of topography in the districts. This could be the explanation that some district have a relatively good or bad starting position in the ABM.

The assumption of homogeneous districts, however, seems fair to one of the experts. The only information that is lost is the possibilities for different water infrastructure that is caused by the terrain and topography in a district. Districts can have flat or rough terrain, resulting in different opportunities for infrastructure, such as the effort that are needed to construct a hand pump or to construct a borehole.

Water infrastructure A first remark from one of the experts is that the total amount of water used in a district is higher, as people in the district use freshwater sources, such as rivers and lakes. These sources are not present in the data that are used for the calculation of the initial water service levels in the model. This would mean that there in practice is more water in the system than is represented in the ABM. It does not mean we have to change any of the analysis in the previous chapter, as the level of stabilisation or the initial conditions would have been higher, but the behaviour would have been the same.

A second remark of the same expert is that the breakdown of infrastructure can represent many things. This is described into detail in this thesis, excluding one thing: the shallow well itself can break down. This causes a whole different form of problem. It could for instance mean that the ground water is too low, resulting in a different form of problem solving than replacing a hand pump.

The assumption that peers down the complexity of the failure of infrastructure to a normal distribution is, according to one of the experts, a fair assumption. The numbers that are used and the spread that is caused seem reasonable based on the experience of the expert. The assumption that water point that are non-functional for a period of 5 years seems reasonable as well and coincides with what one of the experts observed in practice. The assumption itself, furthermore, is based on an assumption that is made by the Ugandan authorities at national level.

District Conditional Grant and investment strategy Regarding the allocation formula, an expert states that districts in practice act very *reactive* in maintenance. The responsible parties at district level do not perform regular rounds of maintenance where every piece of infrastructure is repaired. In practice the party receives a message about non-functioning water infrastructure and after that planning and maintenance efforts are performed.

The allocation formula in the model is an abstraction of the allocation formula used in the rural water supply system in Uganda. As described in chapter 4 the formula is simplified to three categories of which one is budget for Capital Maintenance Expenditure. I assume that districts annually reserve a part of the budget in the District Conditional Grant for CapManEx. In practice district do not make a conscious decision about expenditure on categories as determined in the District Conditional Grant, instead the districts file a Work Plan, describing the projects they want to perform in a year. This means that in the model districts are assumed to make a conscious choice about the type of investments, whereas in practice districts make a conscious choice on what products the budget is spent.

Second, it seems logical according to an expert that under the current implementation of the policy that determines the budget the districts receive, the districts in practice won't report above the national average. This would result in a punishment for good performance. This type of behaviour is not present in the ABM.

Another dynamic that is not present in the ABM is signalled by another expert: in a case of financial allocation it is not desirable for a district to deliver worse than their projections. There is a negative connotation with under-performance. Also, not spending all your budget can in practice lead to a lower allocation in the next years. These two dynamics are not represented in the ABM.

Another remark about the budget that the districts receive concerns the geographical representation of the districts. The districts are geographically the same. The budget that the districts receive is assumed to be the budget that the actual district in Uganda receive. These budgets, however, account for the geographical differences in the districts. In other words, a district with a relatively more difficult topography receive more budget than a district with a more easy topography, to account for the difference in ease of implementation of water services. This means that the districts are considered homogeneous, but the budgets they receive are based on the heterogeneity of districts that is observed in practice.

Selection method In a discussion about the selection method that is used in the model, i.e. the method that is used to determine whether an allocation ratio is performing good or bad, one of the experts mentions that the definition of good and bad policies is an assumption as well. It is good to be aware of the latter. If the assumption of good and bad performance is not good, districts might learn the wrong things.

Another remark from an expert that connects to the previous is that the ABM does not consider what makes a district perform well. It could be that the ratio makes the districts perform good or bad, but it can also be the result of many other things in practice: for instance the availability of fresh water sources, the practising of good governance, or a stable political situation.

Next, the ranking method is based on assumptions as well. In the selection method districts are ranked highest to lowest, based on the water service levels provided. The method of ranking is **not** a method that is currently used in Uganda. The method of ranking is deducted from Blue Drop System in the Republic of South Africa [Department of Water and Sanitation, Republic of South Africa, 2016].

An expert mentions that the assumption that districts have full information is not far from the real situation, especially not when you consider time steps of a year. Maybe it doesn't reach up to the district level, but when infrastructure is broken the experience of the expert is that people will complain and report the failure. A paper trail might be absent, but there is definitely movement in the users of the water point.

Replication method First, the learning venues at the regional level are recognised by the different experts. A learning venue that is initiated by the Technical Support Unit is added: the Inter-District Meeting. In this meeting the goal is to share best practices between all districts within a TSU region. Another remark, however, states that it can take a very long time before the regional learning structure is effective. A regional actor can initiate a learning venue for the different districts, but it takes time before the districts trust the forum and each other.

Furthermore, the role of the Technical Support Unit in the description of the national learning structure is recognised as a process that occurs in Uganda. The best example of this communication structure is provided by the case of the Hand Pump Mechanics Association. In this case the foundation of a hand pump mechanics association in one district is picked up at regional level by the Technical Support Unit and subsequently spread to all other districts by means of an undertaking set at the national level.

A third remark from an expert is that the replication process is actually all about the communication tool that is used. Some tools have more power and reach more people, e.g. a law or undertaking. Therefore you have to consider the communication tools that are available to the different levels.

Variation method In the variation process we have to reflect on the formula that is used in the *random fractional* implementation. The formula is used to represent conscious and unconscious processes of adding variation. It can change both the ratio for CapEx and CapManEx. According to one of the experts a reflection on the formula and what it should represent is needed to trust the outcomes of the analysis of the variation processes in the experiments.

8.2 Expert Reflection on Model Behaviour

This part discusses the expert reflection on the behaviour generated by the ABM. We discuss the generated behaviour to validate whether the output of the ABM can be translated to the real system. The validation of model behaviour led to numerous discussions. This section captures the essence of the discussions by describing the discussions about the general model behaviour, about the scenarios for replication and variation method and about the experiment with the loosened restrictions of the allocation ratio.

General Model Behaviour This part mainly reflects on the discussion invoked by Figure 7.1, that shows the aggregated district performance of all simulations in lines and in a box plot. We observe that the water service levels decline in the first 5 years from 19 to approximately 14 litres of water per person per day. Second, we observe that the water service levels stabilise after that time.

An expert emphasises his belief that the sector is driven by money. If more money is put into the system, the service levels stabilise at an higher service level. Therefore, it is hard to validate whether the current water service levels in the output of the ABM are realistic. There are many assumptions made and the level at which the system stabilises is, under the assumption that the system is mainly driven by money, a direct consequence of those assumptions. This leads to a discussion that is not about the level, but rather about the behaviour of the system. The expert expected the system to have service levels that continue to drop, however, the ABM output shows a stable behaviour. A possible explanation is the assumption that financial resources of districts continue to grow at the same pace as the population growth.

Another discussion concerning the general model behaviour is about the starting position. The initial remark of two of the experts is that they expected that the starting water service level would be lower. The initial level is a function of the assumptions and data that originate in Uganda. This means that it could also be that the level at which the system stabilises is too low, and assumptions that result in that level are inaccurate. The explanation for the steep drop of the water service levels seems to be that there is not enough budget for CapEx and CapManEx to maintain water infrastructure and build new water infrastructure to stay at the current level. Another cause mentioned by one of the experts is that there has been an enormous infusion of money in the sector. If the ABM is only relying on the District Conditional Grant, money from donor organisations is excluded, which could cause the difference between the stable water service level and the initial service levels.

Finally, about the general model behaviour, some remarks are made about the validity of the aggregation level in the model. Since the model does not consider the granularity of county, village and individual water point level, interpretation of the model behaviour might be flawed. There is a discrepancy between how the actual service levels are measured and how they are measured in the model. This discrepancy also exists in Uganda between how the service levels are measured at sub-county level and at national level. At national level an assumption for the number of people that a water point can serve is used, e.g. a borehole can deliver water services to 300 people, when 500 people use the borehole national level considers the coverage 60%, as 200 people do not have access. At sub-county level the people who are not served actually use the borehole as well. It might cause that people have less water on average or it might cause higher chance on a malfunctioning water point, but this statistic is not considered at national level. One of the experts concluded that when the system is aggregated at district level, the Ugandan government is wrong about the coverage numbers in the country. The financial policy of national government is designed to reach higher coverage in the country and therefore the policy is focussed on budget for investment in new infrastructure that can serve people without access to water of sufficient water service levels. When aggregated at a system level, the current water infrastructure can account for 19 litres of water per person per day. This means that the financial policy should be focussed on maintaining the current infrastructure, rather than building new infrastructure.

Scenarios for Variation and Replication The different scenarios for learning, described in chapter 6, are subject of discussion in this section. The experts are shown Figure 7.5, Figure 7.8 and Figure 7.10, figures that exhibit the behaviour of different scenarios for the implementation of memetics in the ABM.

An interesting remark is that all experts found it difficult to predict the behaviour for the different scenarios. One expert predicted that the scenario of national learning would not work very well, as the districts are too heterogeneous for a single policy to work for all of them. Second, a remark is made in reflection that the effect of learning is marginal compared to the financial resources that are available in the system. Good and effective learning methods contribute to progress in the sector on water service levels, but finance is the main driver of the behaviour.

An expert mentions that the different methods for replication result in a big difference. A possible explanation for the greater spread of the fully rational replication method is that a policy is spread quicker and therefore the system might be more sensitive to the starting conditions of the ratio which are assigned randomly. A method to verify this statement is to, intentionally, set the initial allocation ratio to *good* or *bad* and verify if indeed the system behaves more sensitive to the initial conditions.

Furthermore, the expert states, we can see that the median of the fully rational method is higher than the myopic method which in turn is higher than the random method. The spread, however, grows in the opposite direction. From the figures that support this claim we can also see that outliers can be really good, but also really bad in the fully rational method. This is where a policy maker should make his decision about.

The expert states a similar consideration about the variation step and what it represents. What you can conclude is that the random fractional method actually performs better: the median is similar to the perfect copy method but the spread is less, i.e. there are no really bad cases. This is what Ugandan government is currently aiming for with their water supply policies represented by the formula that decides how much budget a district receives.

Loosened Conditions for Allocation Ratio A result of the last paragraph in the section on general model behaviour was that the discussion with one of the experts led to the hypothesis that the conditions in the financial allocation from national level might cause the level at which the system stabilises. This was before Figure 7.12 was shown. The expert valued the financial insight the modelling efforts creates at the least as much as it enlarges understanding about learning in the sector.

While discussing the implications of the model simulations with the loosened restrictions with another expert we came to the point that it is a moral discussion. There are different performance indicators: water quantity per person versus coverage. Based on a preference for a performance indicator you can reach different conclusions. Will you invest the budget in such a way that there is more water produced, ignoring the geographical distribution of the water? Or will you invest your budget in such a way that most people have access to water? And do the two exclude each other? This research can give Ugandan policy makers the handles to start such a discussion.

9 | Conclusion and Reflection

In this chapter I present the conclusions of the research and I provide a reflection on the research. In this thesis we have seen how we can decompose learning and apply it to a Socio-Technical System. The decomposition of learning is applied to a specific Socio-Technical System - rural water supply in Uganda. A dynamic representation of learning is simulated in an Agent-Based Model with the use of memetics. The conclusions about the applicability of modelling learning in order to enhance understanding of learning processes in a water supply system and the methods used in this thesis are presented in section 9.1. I chose to separate these conclusions from the conclusions that specifically apply to Uganda. The financial allocation in the Ugandan rural water supply sector was a suitable case to test the conceptualisation of learning. In the process of modelling, many insights about the governance and policy framework in Uganda are generated. These insights are discussed in section 9.2. Next, I discuss a number of limitations of the research in section 9.3. My own resources were limited, therefore, I had to make choices in this thesis. After the main conclusions, the insights generated for the Ugandan water sector and the research limitations I point to the main contributions of this research to modelling learning in water supply systems in section 9.4. I do this, because it enables the reader to value different parts of the research and use it for own purposes. In the final part of this chapter I include some categories that I recommend for further research based on the findings in this research. In section 9.5 we can read for example that a focus on different institutional levels and a different implementation of learning can complement the findings in this research.

9.1 Main Conclusion of Research

Before we go into the conclusions let us first revisit the main research question of this thesis. In chapter 1 we set out to understand the role of learning on the water service levels in the rural water supply sector in Uganda. We identified that both the individual and the system as a whole are able to learn and that the second is often a result of the first. Agent-Based Modelling as a method to understand learning in rural Uganda entered the thesis, because of the applicability of ABM to capture emergent behaviour of a system as a result of individual learning processes. The research question was formulated as follows:

"How to conceptualise and model learning and its effect on Water Service Levels in the rural water supply sector in Uganda?"

The answer to this research question and the conclusion of this thesis consists of multiple parts. I first reflect on how learning processes in a water supply system can be understood. Second, I conclude on the applicability of memetics to conceptualise and model learning and the effects of learning on water service levels in a rural water supply system, supported by findings from the Ugandan case study. Third, I describe the findings about learning in this research in the light of growing uncertainty and complexity in Socio-Technical Systems in general and in the Ugandan case study.

For the construction of a conceptual model of learning between different actors in a water supply system two concepts are crucial: the core concepts of learning and understanding of the governance situation in the socio-technical system of interest. Learning on it's own is an abstract process. There are many different perspectives on learning and the way that is learned. Learning in an institutional environment with multiple actors is even more complicated, as it includes learning that originates in the interactions between actors. The first consideration to *bound* learning in this thesis was the definition of learning as the ability to recognise signals and act appropriately in response. With this focus a decomposition of learning was still needed: what actors can learn, what do they learn about and how do they learn? Understanding of this breakdown of learning is needed to make the step towards the way in which policies are shared between different actors.

Having made the decomposition of learning, and understanding the core concepts of who can learn, what they learn and how they learn it, the modeller can apply the matter to the system of interest. The first step is to understand the system of interest. In this thesis the system is described as an STS. The governance situation is crucial in understanding the system: what actors are involved, what are there responsibilities, what power do they have, and how are they influenced by limitations such as rules and laws? In the process of modelling a modeller is forced to understand and recognise learning processes and structures that enable learning in a sector. In a multi-level governance environment these learning structures can be messy and identifying the structures and processes as well as describing the lack of clarity around them already adds value to the understanding of learning in the system.

This research contributes to the understanding of encoding learning in an ABM. In this research learning processes in a water supply system are encoded into an ABM. Describing these learning processes as processes of cultural evolution and describing them by the theory of memetics enabled the encoding. The notion of a *meme* as the subject of evolution in a multi-level governance system allows the analysis of the spread of policies through the sector. The necessary conditions for a loop of evolution - selection, replication and variation - forced me as a modeller to make clear choices in the conceptualisation phase. One of the arguments for memetics is that the processes of selection, replication and variation would allow for a structured reflection of the applicability of the methods used in the ABM. For every step the use, the insights and a reflection on the core model assumptions for the part is given. An overview of the assumptions that were used to model the learning processes with memetics is presented in Table 9.1.

First, the selection process demands for an indicator of performance - assumption 11 - and an unambiguous definition of good and poor performance to determine what memes are selected to *live on* and what memes are considered less fit to the environment and *cease to exist* - assumption 13 and 14. In reflection on assumption 11, stating that the indicator of performance in the ABM is water quantity aggregated at district level, we can conclude that there are many ways to measure performance in a water supply system and that there is often no unambiguous use of performance indicators. In Uganda alone a variety of six performance indicators are identified: coverage, functionality, water quantity, water quality, accessibility and reliability. These are all used interchangeably by different actors in different contexts. A second conclusion here is that data on the performance of districts are crucial for the selection mechanism to work in practice. Assumption 12 states that we assume in the ABM that districts have complete information about the state of their infrastructure. In practice, there are many structures or systems in place that support the monitoring efforts, however, they seldom provide data that are complete and up to date. The definition of good and bad performance in the selection process is based on infrastructural data. Without accurate data, I expect that the concept would function less, as good policies might remain unnoticed due to inaccurate monitoring.

Assumption Number	**Content of the Assumption**
11	The water service level in a district is measured in litres of water per person per day, aggregated at district level
12	District have full information about the state of the infrastructure
13	Allocation ratios are selected based on a ranking and on the nationally set target water quantity
14	Allocation ratios that are considered bad are not replicated, i.e. they *cease to exist.* Good allocation ratios are replicated, i.e. they *live on*
15	Districts replicate another ratio when they are performing poor. The ratio they replicate is the ratio of the top ranked district under the conditions of fully rational, myopic or random
16	When districts replicate an allocation ratio from another districts, they vary the selected ratio by making either a perfect copy, or adjust the ratio with a random fraction between the selected ratio and the ratio used in the previous year

Table 9.1. Overview of Assumptions in Learning Conceptualisation Phase

Second, the replication step provides the opportunity to consider and test different scales of learning processes. In the case study the replication process is used to observe the relation between the institutional levels involved in learning processes and aggregated system performance. Assumption 15 describes that the districts with poor performance replicate the ratio from the best district within sight. The different scales of the learning structures are represented by the scale of the vision of a district - random, myopic or fully rational. The replication step moreover enables to observe the relation between learning in a system and the output of a system. The case study shows the possibilities to capture different structures in the replication process of memetics and simulate the effect of the structures over a period of time to analyse system behaviour. Based on the case study we can conclude that the larger the vision of a district, the better the system performs and the higher the variation of the outcomes.

Furthermore, the replication step can be used to draw conclusions about the roles and capacity of the actors and institutional levels that are modelled in the ABM. In the ABM actors are assumed to have a certain role and certain capabilities. The Technical Support Unit, for instance, was considered to be able to identify effective policies in all districts in Uganda. This assumption was made in the fully rational replication method and it assumes that the TSU has the capacity to do this. In practice the capacity of the TSU to monitor all districts in Uganda is questionable. In analysing the isolated effect of a learning structure we can see how well it performs given that the assumption about the capacity or role of the actor. A policy maker should reflect on the role and capacity in practice and use this information to focus resources on the right actor for the right purpose.

Third, the variation process is meant to describe how an actor can adapt a policy from another actor and adjust it to its own fitness landscape and the process represents how unconscious addition of variation to a ratio influences system performance. In assumption 16 we see that we analyse the difference between simulations where actors did not change the ratio and simulations where the actors moved from their previous policy towards the newly selected policy. We observed that the interpretation very much occurs in the context of the replication method. The implementation of the variation method make that the methods either support the extremes of the replication method (perfect copy) or contain the effect (random fractional). The question whether it is better or worse to adapt a policy is difficult to answer, making it difficult to draw a conclusion about the absolute effect of the different methods for variation. On the one hand we see that in the random fractional method the unconscious addition of variation to the policy ensures that changes in policy are not radical, as they on average stay closer to the current policy of the districts. On the other hand, we would expect that the conscious adjustment of a policy should result in better performance on average, but we don't see that reflected in the model outcomes. In reflection on the work we learn what might enable better implementation of the variation process of memetics. Better in the sense that understanding about learning processes can be enlarged with the variation process. In order to apply the variation method so that we can draw conclusions about the difference between a policy maker that makes the conscious decision to adjust a policy from another district to their own situation and a policy maker that does not, the variation method should include a state-action pair. A policy maker needs to consider the state of the own system (e.g. geographical, infrastructural) to the state of the area where the policy was considered successful. This allows for rational decisions about adapting a policy in the variation procedure by policy makers. A more extensive description of how I envision this step is given in the recommendations for further research in section 9.5.

The motivation for research into social learning and learning processes in a sector was given by the need to deal with present and future uncertainties in complex systems, as described in chapter 2. Learning provides the opportunity to raise adaptability of actors in a sector, thereby, if successful raising the systems resilience to external perturbations. The learning structures as they are used in the replication process enable us to reflect on learning in a water supply system as a means to deal with current and future uncertainties. First, there are different scales represented in the learning structures: inter-district, regional and national. We have observed that a national learning structure results in a faster spread of policies under the assumptions in the ABM. However, we have also seen that the larger the scale of the communication, the higher the uncertainty in the aggregated output of the system becomes. This is due to the fact that the system is more sensitive to initial conditions (is a policy of a well-performing district a good policy for all districts?). The simulations show that smaller scale communications result in more stable system output. Note that I don't make a hard conclusion here, as I did not test the ABM in reaction to external perturbations. Second, the scales of learning in practice are used in parallel: districts communicate with other districts, the next week they join a regional meeting and for instance every year the national government mandates a new policy that originates in one of the districts. Note that there are two new factors to consider if we want to draw a conclusion about the ability of a system to deal with disturbances: parallel use of learning structures and the speed of learning structures. In conclusion, this thesis shows that in order to deal with external disturbances in a system a policy maker has to consider scale, speed and the parallel use of learning structures. Based on this research I cannot draw a hard conclusion on the optimal implementation of the three. I do show what effect the scales of learning can have and what considerations policy makers should make and I do show what other factors policy makers have to consider: speed and parallel use of learning structures. The handles that a policy maker has in considering learning structures as a means to deal with present and future uncertainties in a system. The implementation should occur along the lines of the goals of the policy makers.

9.2 Reflection on Case Study Insights

Besides conclusions about the efforts to conceptualise and model learning processes in rural Uganda a number of insights are created for the sector itself. This section is purposefully named *reflection on case study insights* as the results are *indicative*, given all assumptions and abstractions made as described in chapter 4. In chapter 1 I state that, besides the research question I answered in the previous section, I have another objective with this research:

Help both the research community and those who work in the Ugandan rural water supply sector to enhance understanding of the role of learning on water service levels in the sector from a systems perspective.

In this section I reflect on the value of the research for those working in rural Uganda. I recommend a discussion at policy level in the sector about a number of insights: 1) a discussion about loosening the now strict limits in the allocation ratio, 2) a discussion about the policy to determine the budget that districts receive on a yearly basis, and 3) some handles to make more efficient use of learning structures in the sector. After this, I reflect on some core model assumptions and their implications. A summary of the assumptions is added in Table 9.2.

The first policy recommendation is to open up a discussion about the restrictions in the allocation ratio. The restrictions of interest in this argument are the maximum of 13% that may be spent on CapManEx and the minimum of 70% of the allocated budget that is to be spent on CapEx. The recommendation is induced by the simulations in the ABM that show a significant change in system output when the conditions in the allocation ratio are loosened. This could mean that there is enough money in the system to maintain and even raise service levels compared to the initial conditions, but the money is not spent effectively. I want to make clear that it *could* mean that current resource management is not effective, as we are comparing two different performance indicators. In this research, or more specific in the ABM, we measure the output of the system in water quantity deliver per person, whereas the indicator that is often used in the sector to base policy decisions on is coverage. The hypothesis is that the coverage performance indicator can be raised under the condition of loosened restrictions. In the simulations with the ABM we have seen that a higher ratio of investments in major maintenance results in a higher number of water points and a higher functionality percentage of those water points. The assumption that water infrastructure that has been non-operational for a period of 5 years is considered abandoned plays a major role here, as this ensures that water infrastructure is not used any longer in the simulations. On the other hand the results show that without the restrictions in the ratio almost all (up to 96%) of the water points that is constructed remains functional.

The question raised here is whether the outcomes are still valid if we analyse the coverage performance indicator in more detail under the condition of loosened restrictions. The discussion I recommend should start at this point. The considerations that are raised concern firstly a discussion about resource management and second a discussion about the moral implications of the policy to support a certain type of resource management. What would be the choice and the argument if a policy maker had to choose between a very efficient form of resource allocation and sufficient water for **all** of the population? The latter would have the disadvantage of a relatively low median performance compared to the first. A first step in collecting evidence to support the decision - in whichever way it turns out - is to research how well the resource allocation method that is assumed to be more effective performs when coverage numbers are taken into account.

The second policy recommendation is to discuss the goals that support the current implementation of the DWSCG formula. The current goal is that *every* person should have access to sufficient water services. The implementation, however, is aimed at reaching the *average* national coverage. We deal with a situation where there is limited budget. The argument to raise water service levels to the average in this context is more comprehensible, considering that choices in resource allocation have to be made. There is another reason that I recommend a discussion about the goal of the budget allocation. The districts have difficulties to reach the yearly progress they aim to make, this can be seen by for instance the yearly unspent budget. First, for the districts that are performing below average this means that many of the district will not deliver water services at the average level in five years time. Second, it is questionable if the districts that perform above average receive enough budget to maintain the level they are at. Both can result in a stagnating or even lower water service level. In practice we have observed a pattern that shows the water service levels are stagnating or slowly growing. Unless the national average level is raised with the policy, the goal of getting all districts to average performance will not result in the current overarching goal: sufficient water services for all.

Furthermore, the current implementation of the policy has some disadvantages for the districts that perform above average. Consider the following: a district that performs slightly above average can have 70% coverage compared to the average that is around 66%. This means that 30% of the population of that district does not have access to sufficient water services. This is not a desirable situation and I assume that this is known to policy makers in Uganda, but the current implementation of the formula does not provide the right incentives. First, it is not clear what budgets districts that perform above average receive. *Some* budget, because it is politically difficult to provide none. It is not clear how much budget this is, nor does the formula state if districts receive less if they start to perform better (even more above average). Second, it provides an incentive for the districts to report other than the real situation. If reporting the real numbers would lead to a major cut in the budget, districts might act strategically.

The third argument here is about the goal underneath the policy. The implementation of the goal is, as stated, not aimed to reach the vision of services for all. Furthermore, next to the reconsideration of the current policy, I advise to consider the long term plans behind this goal. What would happen if all districts reached national average? What is the next step? The system is evolving, the districts and the infrastructure is evolving, and the goal or vision behind the budget allocation should evolve with them.

The third policy recommendation is to foster the learning structures that are used in this research, to monitor them and to learn how to benefit from them. The first argument to discuss is a consideration of the institutional levels in Uganda compared to their use in the ABM. The institutional levels in Uganda are conceptualised and abstracted to the agents that represent institutional levels in the ABM. Numerous assumptions about the role, possibilities and capacity of the institutional levels are made. This enables to draw conclusions about the actual institutional levels in Uganda. The role and authority of the regional level in Uganda, for instance, is ambiguous and responsibilities are not clear. The ABM assumed a certain authority of the regional level and simulations with the ABM show that with this authority the regional level can foster learning efforts. Therefore I can advise a discussion about strengthening the role of the regional level in Uganda, as this study indicates that learning at a regional level provides the opportunities for better spread of good policies. I want to give a similar advice for the capacity of the Technical Support Unit. In the ABM, the TSU has the capacity to construct a national ranking and the TSU is assumed to search and find good policies in the districts. Under these assumptions, simulations with the ABM shows that this supports social learning and the spread of policies between districts at a national scale. A discussion about the capacity and role of the Technical Support Unit similar to the assumption in the ABM is a direction to pursue.

Second, policy makers in Uganda can use this research to analyse and monitor learning structures in terms of scale, speed of the learning cycle and optimal parallel use of learning cycles. In this research these three aspect of governance structures that foster learning processes had to be made explicit and a number of assumptions was made to do so. These assumptions can be translated and implemented or tested in the real system.

This section is concluded with a short reflection on some critical assumptions. The assumptions that are made to conceptualise the Ugandan water system are summarised in Table 9.2. In the second policy recommendation we have already seen that two critical assumptions - 1 and 9 - have a big influence on the system behaviour. The way the budget allocation is implemented in the conceptual model is an artefact of the findings about the policy. Furthermore I expect that the assumption that the budget the districts receive grows with the same rate as the population growth determines the system behaviour. This makes that the districts can find a balance between investing in infrastructure and the failure of infrastructure, causing the stable performance.

Second, assumption 3, 4, 5, 6 and 7 represent how the water infrastructure and the geographics of rural Uganda are conceptualised. A reflection on all of them combined is that I expect that it doesn't change the *behaviour* of the ABM and the conclusions about learning in this research. The assumptions mainly influence the amount of resources that the district posses or lack. In the simulations we have seen that the level at which the performance of the districts stabilises depends on the financial resources and the assumptions connected to the costs and lifetime of water infrastructure. Furthermore we have seen in the expert reflection that the districts are assumed similar in geographics (assumption 3), but the budget that the districts receive in the ABM includes geographical considerations as these budgets are based on the budgets of the actual districts (assumption 9). In reflection this might have caused initial conditions for districts that are not proportionate to their actual situation. Performance can be more extreme and this enables situations where bad policies are spread to many districts in the fully rational replication method. However, the type of conclusions that is drawn about the policy insights for Uganda and the policy insights for modelling learning do not change because of the combination of assumptions, as I expect the difference in aggregated behaviour of the districts to be marginal.

#	Content of the Assumption
1	National government has infinite budget
2	Residual budget at district level is returned to national level every year
3	Districts are all the same in terms of possibilities created by geographical characteristics
4	All water points in the ABM are shallow wells operated by a hand pump
5	Failure of a water point is normally distributed with a mean of 6 years and a standard deviation of 1.5
6	A major maintenance operation of a water point entails the complete replacement of the hand pump
7	A water point that is non-functional for a period of 5 years is considered abandoned
8	The allocation ratio is composed of three factors: X (ratio of CapEx), Y (ratio of CapManEx) and Z (ratio unspent budget)
9	The budget allocated to districts is based on the actual budget in Financial Year 2015/2016 and grows with the same rate as the population growth
10	Districts spend all budget without considering the status of the infrastructure in their district

Table 9.2. Overview of Assumptions in System Conceptualisation Phase

9.3 Limitations of Research

In this section I reflect on the limitations of this research. I reflect on critical choices in the thesis to pursue one direction instead of the other. The limitations are ordered by the scale and the impact of the limitation: from critical choices in the ABM to choices about the focus country of the case study. The choices discussed are 1) the choice to implement learning with memetics, 2) the representation of a policy, 3) the choices that concern the governance situation that is analysed, and 4) the choice to demarcate the water supply sector in Uganda.

The first limitation concerns the conceptualisation and implementation of learning. In the research I decomposed learning for who learns, what they learn and how they are able to learn. In application to the rural water sector in Uganda I chose to implement the dynamics of learning using a perspective of cultural evolution that lead to the implementation of memetics. Considerations for who learn and how they learn were made in relation to the case study. I chose for memetics, because in memetics the subject of analysis is a meme, which enables the analysis of the spread of a policy, rather than individual actors learning. The second reason to choose memetics was that the evolutionary processes of selection, replication and variation support the process of encoding in an ABM and provide the handles for extensive reflection on each of the processes. Third, I choose memetics because modelling learning with memetics in an ABM is a relatively unexploited field of study. By choosing for memetics I also made the choice not to model other mechanisms that describe learning processes. The choice has implication for both the findings about the applicability of ABM to model learning processes in rural Uganda and the findings for Uganda itself. For instance, in a learning method that is focussed on an actor rather than a meme, the research might have resulted in conclusions directed at individual actor learning processes and how to foster them, rather than conclusions about the learning structures. This does not mean the conclusions about learning in this research are any less valid, but that the choice of implementation matters for the type of outcomes and that other research could generate other insights.

If we go deeper into the implementation of memetics as a method to encode learning we find some important choices as well. The current implementation is based on the three basic steps of evolution: selection, replication and variation. The implementation of these steps proved to generate the insight that I was looking for, but other implementations might have worked as well or might have generated slightly different insights. Even the choice for the implementation of memetics along the line of the basic steps of evolution can be disputed. Other implementation might for instance consider how ideas are combined in a different way, for instance along the line of dominant and recessive memes.

The second limitation is about the representation of a policy in the case study. In the ABM we selected a meme as object of interest. The policy that determines on what districts spend the allocated budget from national government is enacted in the form of an allocation ratio. The allocation ratio is used in this research to represent how policies in general are spread through the rural water system. Therefore a reflection on the extent to which the allocation ratio represents policies in general is a logical step. The allocation ratio is a good representation of a policy, because every district implements the policy every year. This enables to analyse how such a policy spreads between all districts in Uganda. The ratio is also suited, because there are degrees of freedom in the policy. Districts can choose a ratio within the boundaries set by national level. This enables districts to learn what policy implementation of the policy works best for them.

However, some caveats can be placed with the allocation ratio. Firstly, the districts in practice do not decide what amount of their budget they will spent on the category or the other. The district determine what projects they will invest in in the coming year, the cumulative of all these projects result in a ratio and this ratio should be within the limits set by national level. The assumption of a conscious decision about the ratio for CapEx and CapManEx is not entirely unfounded either, as district have the possibility to consciously choose their project with the philosophy about what ratio works well in mind. Second, the relationship between a certain allocation ratio and output in the system is clear-cut. In practice we observe that the relation between a policy and its effect in the system is not as clear. This has to do with the similar representation of all districts and the choice for a financial policy. In this financial policy there is a clear direction on what is a *better* way to allocate the budget, e.g. spend as less as possible on unspent budget, spend as much as possible on CapManEx budget. This guideline can be used for every district. In practice the relation between the policy and its effect in the system differ from district to district, depending on specific environmental variables in the district. The limitation connects to the third limitation that is described and it provides some suggestions for future research (section 9.5).

The third limitation is induced by the choice of institutional levels in Uganda. This is important in two ways. First, in chapter 3, the Ugandan environment is conceptualised as a multi-level governance situation characterised by multiple institutional levels. These levels reach from national level to community level.

In the application of learning I chose the higher institutional levels in Uganda, i.e. district, regional and national level. This has implication on for instance the representation of geographical factors and the variation in water infrastructure that can be observed in the lower institutional levels. Another example is that failure of water infrastructure is encoded in the ABM by means of a distribution function, whereas in practice there are many dynamics influencing the failure of water infrastructure. The choice for scope was made to understand social learning processes at higher institutional levels, but only allows for analysis of aggregate system performance without considering the specific causes. The loss of the specific information can also be seen in the representation of a policy as discussed in the previous paragraph. Information that make districts different from each other is lost in the conceptualisation. Their differences are exactly what is needed to analyse the spread of policies which will probably lead to a less clear-cut relation between policy and output.

The second important limitation considering the choice for institutional levels is that I considered the governance situation in Uganda to be stable. In practice governance structures are subject to change over time. Pahl-Wostl et al. [2007] emphasise this by stating that governance structures and learning processes mutually influence each other. The research does not include adaptive cycles of policy change [Gunderson and Holling, 2002], nor any non-adherence to policies or governance structures by the actors. Furthermore, I choose to model learning in the rural water supply sector in Uganda. First, rural water supply is not a standalone sector. It is connected to urban water supply, but also to many others such as the health care sector. Choices in the rural water supply sectors are reflected in adjacent sectors and vice versa. An example is the political choices that are made to finance certain sectors more than others. These dynamics are not considered in this research. The simulations run over a period of 20 years and in this timespan changes in political priorities certainly occur.

A fourth limitation is found in the choice for rural water in Uganda. I choose a financial case in rural Uganda. Insights generated by the methods I use here, might differ from applications of the method in different countries. An example is that the multi-level governance environment in Uganda allows a certain type and implementation of the modelling, making memetics a more suited method. The applicability in other water supply systems, either rural or urban, is not proven. Therefore I would advise (section 9.5) to apply the method to model learning processes in an ABM with memetics to at least two other rural water supply systems and preferably an urban system too.

9.4 Contributions to Research Domain

This research makes a number of contributions to encoding learning in systems characterised by multi-level governance. First of all, the research makes a clear delineation of a fuzzy concept: learning. In the research the concept of learning is broken down to its core components. Researchers can use this research to understand who in a system can learn, what they can learn and how they can learn about the matter. This decomposition of learning is not only applicable in rural water supply systems, but I expect in any water supply system and I also expect the decomposition to be applicable beyond water systems, as long as there are multiple institutional levels involved in the matter of interest.

Furthermore, this research emphasises the necessity of learning in a system. The research started with understanding the need for sector research into *a sector that is able to learn and adapt*. A theoretical perspective on the positive effects and therefore the motivation for learning and adapting in a sector is given, namely the growing complexity and uncertainty that is inseparable from Socio-Technical Systems. Numerous suggestions and theoretical concepts that describe how a system through learning is able to become more resilient are described and explained in the context of this research.

Second, in this research this delineation of learning is applied to a system that is fuzzy as well. The governance structure in Uganda is complex: it can be described as an adhocracy with many institutional levels and many peculiar structures and rules. In the research the organisation of rural Uganda is represented in a relatively simple way that describes how the sector works. I described the water sector through a systems perspective and successfully represented the sector as a Socio-Technical System. Successful in the sense that it adds to the current understanding of the reciprocity between infrastructure and the governance structure. Representation of the system as a Socio-Technical System furthermore allowed to apply the theoretical concepts to the Ugandan water sector: not so much in the eventual encoding of the system, but the more in generating understanding of uncertainty in rural Uganda and reflecting on the outcomes of the modelling efforts in the light of the growing uncertainty and accompanying urge to learn and adapt.

In application of learning to rural Uganda three institutional levels are zoomed in on. The application of learning is focussed on how actors in the system can learn from each other. The research describes structures that foster learning processes in Uganda and abstracts them into three institutional levels. In a multi-level governance environment these structures can be messy and identifying the structures and processes as well as describing the lack of clarity around them by itself already adds value to the understanding of learning in such a system.

Third, in this research I managed to encode learning processes in an Agent-Based Model using theory of cultural evolution. One of the arguments to use memetics is that this field is relatively unexploited. In this research we see a successful application of memetics in an ABM to understand learning in a rural water supply system. A meme is conceptualised in a financial case study and enabled analysis of different learning structures. In the research clear choices are described to encode learning using three basic steps in memetics: selection, replication and variation. Each of the three steps can individually be reflected on and used in similar or slightly different ways in other research.

9.5 Recommendations for Further Research

In this research valuable insights are created for the possibilities to understand learning in a water supply system by using Agent Based Modelling. I advise to exploit the current implementation of memetics and I advise to explore other opportunities to model learning processes with the aim to understand the relation between learning and system output in a system. In this section a number of considerations are provided that give directions in which future research should be headed. The topics for further research are in part connected to the limitations that are mentioned in section 9.3. This makes sense, as the limitation that are described concern conscious choices to head in one research direction instead of the other. Some of the considerations for further research described in this section explore the paths that were not taken in this thesis.

The first recommendation is to *exploit* the possibilities of memetics to understand learning in a water supply system. Firstly, by considering a different policy. In this thesis the policy of interest in the ABM is the allocation ratio. In this financial policy there is a clear direction on what way to allocate the budget is *better*, e.g. spend as little as possible on unspent budget. Furthermore, this conclusion is similar for every district in the country, as they are modelled in a homogeneous manner. The relation between a policy and the output of the system based on that policy is clear-cut and is the same for every district. In practice the relation between the policy and its effect in the system differ from district to district, depending on specific environmental variables in the district. Therefore I advise to replicate the research using memetics with one or multiple policies that is/are heterogeneous in the output they generate among the actors.

The second recommendation that exploits the possibilities of memetics is to focus on different institutional levels. In this thesis the focus is on district, regional and national level. Thereby the choice is made to simplify most of the granularity of the processes at lower institutional levels. This simplification is for instance translated to the considerations about water point breakdown and the assumed homogeneity of the districts. The choice for scope was made to understand social learning processes at higher institutional levels, but only allows for analysis of aggregate system performance without considering the specific causes. The loss of the specific information can also be seen in the representation of a policy as discussed in the previous paragraph. Information that make districts different from each other is lost in the conceptualisation and this is exactly what is needed to analyse the spread of policies with a less clear-cut relation between policy and output.

A third recommendation that exploits the possibilities of memetics is to replicate the research. In this thesis memetics is applied and encoded on one specific system: rural water supply in Uganda. It would first of all be interesting to see how this implementation performs in other, similar rural water supply system. This adds understanding to the possibilities for encoding learning with memetics and the type of insights it can generate in systems such as rural water in Uganda. Second it would be very interesting to see a similar implementation in another system, urban water supply, systems in other countries or in sectors other than water. I assume that with these kinds of research we can advance our insight into the applicability of memetics as a method to understand learning in a system and what types of insights can be generated given characteristics of the system of interest.

The second recommendation for further research is to *explore* the relation between the governance structure and learning processes in a system. In the thesis I assumed a stable governance structure, whereas evidence suggest that there is a relation between learning and the governance structure [Pahl-Wostl et al., 2007]. Learning and the governance structure mutually influence each other. Defining these relationships and implementing them in a computational model, such as the one used in this thesis, can help in analysing the effect of the relationships and the variables influencing the relationship. Such a research can complement this research as it includes more of the actual dynamics in a water supply system that was considered stable in this thesis.

The third recommendation is to *explore* the possibilities with a different implementation of learning. In this thesis we have seen how the implementation of learning using theory on memetics resulted in some valuable insights in the water supply system of interest, for instance about the isolated effect of learning structures or the advice to reconsider the restriction in the allocation ratio. The choice to implement learning processes with memetics was also a choice to not use any other conceptualisation of learning. Consequence of this choice is that we found a certain type of insights about the possibilities to encode learning in an ABM, namely insights at the governance level of a system. We analysed for instance the effect of the scale of learning structures and of a national selection mechanism for performance. A different conceptualisation of learning might have led to another type of insights. A learning method that is focussed on an actor rather than a meme might have resulted in conclusions directed at individual actor learning processes and how to foster them.

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Appendices

A | Detailed Model Specification

This appendix provides a detailed model specification of the ABM. In chapter 4 the conceptualisation is described. The ABM is implemented in NetLogo, where the conceptualisation is abstracted to lines of codes. This appendix guides you in two steps from the rough conceptualisation of a model representing learning in rural Uganda to the eventual code. The first step is a so-called *model narrative* in section A.1, which basically is a story of what happens in the ABM procedures: what does which agent do when to whom and why? In the second step we turn the narrative a step closer to code. The *pseudo-code* is a good means to implement the ABM with less mistakes. The pseudo-code forces a modeller to make the step to the concepts and terminology that is used in the Netlogo environment, thereby making clear implementation choices. This second step is described in section A.2.

A.1 Model Narrative

The model narrative consists of two parts. In the first part I describe how the initial situation for the simulations in the ABM is created: the model set-up. In the second part the procedures are described. This is the section that described the actions and decision rules of the agents during the simulations.

A.1.1 ABM Set-up Procedures

The first step is to clear all information from previous runs.

Set-up national level The number of districts in the country is set at 110. Some parameters that apply to all levels in the country are set, e.g. the price for CapEx and CapManEx, the Average District per Capita Cost of water service delivery, the rural population growth, the target water quantity sand the delivery capacity of a WP.

Set-up regional level All the Technical Support Units (TSU) are created. The TSUs are given a number and a geographical and a graphical representation in the NetLogo world.

Set-up district level A total of 110 districts are created. The districts in the model represent real districts in Uganda, except for Kampala, as this district is a town and has no rural characteristics. The parameters of the district are set similar to the values in the real district. Next, the districts are placed in the TSU they are in and receive a number between 0 and 109 on alphabetic order from the district names.

All districts receive a number of WP that delivers approximately the same amount as was delivered in the actual district in 2015. All WP in the model, however, are considered to be of one type. A shallow well. The water quantity these WP in the model deliver corresponds to the total water quantity delivered by all the different types of WP in the real district.

The water quantity per person in the district is calculated based on the number of WP and the water quantity they deliver, the functionality percentage of the WP in the district and the population. This result in a water quantity per person measured in litres per person per day. Water quantity per person in the model is the representation of the water service levels.

Each district sets a random allocation ratio within the boundaries set by national level. The districts use the allocation ratio later in the simulation to determine the amount of budget that is available for CapEx and CapManEx expenditures.

The district set the District Conditional Grant. The DCG is not calculated in the model, it is the amount that is granted in the financial year 2015/2016 by the MWE. The DCG will grow with the same rate as the population growth.

Create Water Points Each district contains a number of WP. All the WP are created and are assigned to the number of the district they are in. A WP delivers services to the district it is in. In the NetLogo world the WP are randomly placed within the TSU region the district is in. The WP get the shape of a water drop.

Each WP determines if it is functional or non-functional. The distribution of the operation-state of the WP corresponds to the functionality percentage of the district. A functional WP is blue, a non-functional WP is red.

Each functioning WP determines its age and its expected lifetime. The expected lifetime is an integer drawn from a normal distribution with a mean of 6 years and a standard-deviation of 1,5 years. The age of a WP is a random number drawn between 0 and the expected-lifetime of a WP.

Each non-functioning WP determines the years it is out of function: a random integer between 0 and 5. When a WP is non-operational for 5 years, the WP is considered abandoned. In the model the WP dies when non-functional years reach 5.

Create a list of districts for each TSU Each TSU determines what district are in their TSU region. These districts are put into a list, this makes the model run faster as subsets of districts can be asked to perform procedures.

Create a list of WP for each district Every districts makes a list of WP that deliver services to the district.

A.1.2 ABM Go Procedures

The ABM is set-up. All agents are initialised and global variables are set according to the model parametrisation. In Table A.1 an overview of the model procedures is provided. The procedures are described below.

Table A.1. Overview of procedures in ABM

Procedure	**Institutional level(s)**
Return budgets and reset rankings	national, regional, district
Calculate water service level	district
Selection procedures	national, regional, district
Replication procedures	national, regional, district
Variation procedures	national, regional, district
District population grows	district
Water Point age	water point
Calculate CapEx and CapManEx budget	district
Districts spend CapEx	district, water point
Transfer residual budget	district
Districts spend CapManEx	district
Update lists	district

These procedures are repeated until the simulation stops. The simulation stops when the number of simulation years is reached. The standard number of simulation years is 20. Below is a detailed description of the procedures.

Return budgets and reset rankings The TSU and the national level reset the rankings used for the selection procedures. Next, the districts return all budget they haven't spent in the previous year to national level. National level is assumed to have an infinite budget, so district reset CapEx and CapManEx budgets and budget spent to zero.

Calculate water service level Districts calculate their service levels measured in water quantity delivered per person in the district. The districts multiply the number of functional WP with the water delivery capacity of a WP. The total water quantity delivered in the districts is divided by the population of the district to calculate the water quantity per person.

Selection procedures The districts are ranked based on the water quantity per person delivered in the district. The districts are ranked from high quantity delivered to low quantity delivered. If the districts are *myopic* a separate ranking is made for each region.If the districts are *fully rational*, having full information of every district in the nation, the ranking is made at national level and includes all districts.

Based on either the national district ranking or the regional district ranking, districts determine if they are the best district in their region. A *best district* is important in the replication procedures. Districts furthermore determine if they are in the bottom half of the ranking. This distinction is again important for the replication procedures.

Based on the previous two districts determine if they use their own allocation ratio again in this year:
1) Based on the previous two districts determine if they use their own allocation ratio again in this year.

2) A best district always uses their allocation ratio again. 3) A district that is in the bottom never uses their own ratio again. 4) A district that is in the top half and is delivering above the target quantity uses its own ratio again. 5) A district that is in the top half, but is delivering below the target quantity uses a ratio from another district.

Replication procedures In the meme replication procedures districts determine what ratio they replicate, if a district determined in the selection procedures to use the own ratio again, the district replicates the ratio it used in the previous tick. If a district does not use its own ratio again the following procedures apply. Districts replicate the allocation ratio of the best ranked district. Either from the best district in the nation - *fully rational* - or from the best district in the region - *myopic*. In a third scenario - *random* - the districts copy an allocation ratio from a random district.

Variation procedures In these procedures the districts can vary the allocation ratio they have chosen to replicate. Districts that use their own ratio again don't vary their ratio. If the variation procedure is *perfect copy* the districts blankly imitate the allocation ratio they have selected. This applies to all different replication methods (fully rational, myopic and random). If the variation procedure is *random fractional* the district vary the replicated ratio with a random fraction. For this the difference in the ratio for CapEx between the replicated ratio and the ratio used by the district in the previous year is taken. This difference is randomised and deducted from the ratio available for CapEx and added to the ratio for CapManEx.

The new ratio is verified on compliance with the rules for the allocation ratio set by national government and adjusted to fit within the set boundaries. If the replication method is random, no variation is added in this procedure.

District population grows The population of the district grows with the population growth rate.

Water points age All WP age a year. Operational WP add a year to their age. If the age of the WP reaches the expected lifetime, the WP fails and becomes non-functional. The counter for years that a WP is non-functional starts. If a WP in non-functional, the years a WP is non-functional grows with one year. If a WP is non-functional for 5 years in a row it is considered abandoned and dies.

Calculate CapEx and CapManEx Districts calculate the budget for CapEx by multiplying the DCG with the ratio available for CapEx in the allocation ratio. Districts calculate the budget for CapManEx by multiplying the DCG with the ratio available for CapManEx in the allocation ratio.

Districts spend CapEx budget Districts spend their budget available for Capital Expenditure. Districts do not consider how many WP are needed to reach target service levels, they blankly spend their CapEx budget on the construction of new WP. Districts first calculate the maximum number of WP that can be constructed with the available budget by dividing the CapEx-budget by the price to construct a new WP. The integer of that calculation is the number of WP the district will create.

New WP are created. The WP are assigned to the right district and the right TSU. Furthermore, they set their age at 0 and calculate their expected-lifetime. They are set to be operational. Districts calculate the CapEx-spent by multiplying the number of WP constructed by the price for construction of a single WP.

Transfer residual budget Residual CapEx budget is transferred from CapEx budget to CapManEx budget. Most of the time there is some leftover CapEx budget. This budget is not enough to construct a new WP. This budget, the difference between CapEx-budget and Capex-spent, is used to invest in major repairs.

Districts spend CapManEx budget Districts spend their budget available for CapManEx on reparation of non-functional WP. Districts calculate the maximum number of WP that can be repaired by dividing the available budget by the price for maintenance of one WP. If a district has enough budget to fix all non-functional WP, the district repairs them all. The WP are operational again, their age is 0 again and they calculate their new expected-lifetime. If a district doesn't have enough budget to repair of non-functional WP, the district randomly selects the maximum number of WP and repairs them. The districts do not consider the years that a WP is non-functional.

The CapManEx spent is calculated by the number of WP that are repaired times the price for one repair. The WP update their colour according to their new operation state.

Update lists Districts update the list of WP that are in their district. The lists are used to speed up all procedures in the next tick in terms of computation time.

A.2 Pseudo-Code: From Narrative to ABM

The pseudo-code is the last step between the model narrative and the code in the Netlogo environment. As can be observed, the narrative as described above already start to look like code. The pseudo-code represents the same steps as the story in the previous section. For a detailed description of the meaning of each line of code I refer to the code in the ABM that contains a description for every line of code.

A.2.1 Set-up model

Set-up model variables

- Create breeds: TSU, district, WP
- Create globals
- Define variables of breeds

Overview of set-up procedures

- Clear-all
- Read file with district parameters
- Set-up national level
- Set-up TSUs
- Set-up districts
- Set-up TSU-district list
- Set-up district-WP list
- Reset-ticks

Read file with parameters from 110 districts

- Open .csv file from directory
- Create empty list
- Read every line of the file, put each line in a list in the empty list

Set-up national level

- Set number-of-districts,
- Set delivery-capacity-WP
- Set population-growth-rate
- Set target-quantity
- Set capex-price
- Set capmanex-price
- Set minimum-Capex-Percentage

- Set maximum-Capmanex-Percentage
- Set national-best-x national-best-y and national-best-z

Set-up TSUs

- Create a list of TSU boundaries for graphical representation
- Create a list of TSU colour for graphical representation
- Repeat for 8 TSUs
  - Create 1 TSU agent
  - Set number
  - Set boundaries and colour from lists
  - Ifelse "number < 5"
    * Ask patches with [pxcor > (boundaries − 1) AND pxcor < (boundaries + 11) AND pycor >= 0]
    * Set pcolor (colour)
    * Set ycor 10
    * Set xcor boundaries + 5
  - Else
    * Ask patches with [pxcor > (boundaries − 1) AND pxcor < (boundaries + 11) AND pycor < 0]
    * Set pcolor (colour)
    * Set ycor -10
    * Set xcor boundaries + 5
  - Set shape, size and colour
- End repeat

Set-up districts

- Read list with lists from file with district parameters, outcome is a list for each of the following parameters: number, TSU-number, name, population, number-of-WP, functionality-percentage and initial-DCG
  - E.g. set di-population but-first item 3 parameterList (first item in the list is the name of the variable in the list)
- Repeat for 110 districts
  - Create 1 district
  - Set number, TSU-number, name, population, number-of-WP, functionality-percentage and initial-DCG from lists
  - Set colour of district the colour of the TSU it belongs to
  - Move to a random patch with that colour

- Set size, shape and colour
- Calculate water-quantity-per-person: ((number-of-WP * functionality-percentage * delivery-capacity-WP) / population)
- Set allocation ratio
  * Set Actual-X (random (100 + 1 – (Minimum-CapEx-Percentage * 100)) + (Minimum-Capex-Percentage * 100)) / 100
  * Set Actual-Y (random (maximum-capmanex-percentage * 100) + 1) / 100
    · If "Actual-X + Actual Y > 1" Set Actual-Y (1 – Actual-X)
  * Set actual-Z (1 – Actual-X – Actual-Y)

- End repeat

Set-up WPs

- Foreach district repeat number-of-WP times
  - Create WP 1
  - Set district number of corresponding district
  - Set TSU-colour of TSU district is in
  - Move to one-of patches with [pcolor = TSU-colour]
  - Set size and shape
  - Ifelse "counter functional WP <= functionality-percentage * number-of-WP
    * Set operation-state 1
    * Set expected lifetime int random-normal 6 1.5
    * If expected lifetime < 0 [set expected-lifetime 1]
    * Set age random expected-lifetime
    * Sel color blue
    * Set non-functioning years 0
  - Else
    * Set operation-state 0
    * Set color red
    * Set non-functioning years random 5
- End repeat

Set-up TSU-district list

- Ask TSUs
  - Set myDistrictList turtle-set districts with [TSU-number = number]
- End

Set-up district-WP list

- Ask districts
  - Set MyWPList turtle-set WPs with [district-number = number]
- End

A.2.2 Go procedures

The ABM is set-up for the simulations. This part describes the model procedures that occur in every tick of the simulation. First an overview of the procedures is provided and second we see the implementation of the procedures.

Overview of go procedures If ticks <= SimulationYears

- reset budgets and rankings
- calculate water quantity per person
- meme selection procedures
- meme replication procedures
- meme variation procedures
- grow district population
- water points age and fail
- calculate capex and capmanex budget
- spend capex
- transfer residual capex
- spend capmanex
- update WPlist and functionality percentage

Tick If ticks = SimulationYears [stop]

Reset budgets and rankings

- set national-ranking-list [ ]

all TSUs

- set regional-ranking-list [ ]

all districts

- set capex-budget 0
- set capex-spent 0
- set capmanex-budget 0
- set capmanex-spent 0

Calculate water quantity per person All districts

- let n count myWPList with [operation-state = 1]
- set water-quantity-delivered n * delivery-capacity-WP
- set water-quantity-per-person water-quantity-delivered / population

Meme selection procedures All districts select-best-district

- if replication-method = "fully rational " or "random"
  - set national-ranking-list lput water-quantity-per-person
  - set national-ranking-list sort-by > national-ranking-list
  - set national-best-district-level item 0 national-ranking-list
- end if replication-method = "fully rational " or "random"
- if replication-method = "myopic"
  - ask TSUs
    * set regional-ranking-list lput water-quantity-per-person of myDistrictList
  - set regional-ranking-list sort-by > regional-ranking-list
  - set regional-best-district-level item 0 regional-ranking-list
- end if replication-method = "myopic"
- ask districts
  - ifelse water-quantity-per-person = national-best-district-level
    * set best district? 1
    * set color yellow
  - else
    * set best-district? 0

All districts select-bottom-half-districts

- if replication-method = "fully rational" or "random"
  - set national-median-district-level median national-ranking-list
- end if replication-method = "fully rational" or "random"
- if replication-method = "myopic"
  - ask TSUs
    * set regional-median-district-level median regional-ranking-list
  - end ask TSUs
- end if replication-method = "myopic"

- ask districts
  - ifelse “water-quantity-per-person < median-ranking level” and “best-district? = 0”
    * set bottom-half? 1
    * set color red
  - else
    * set bottom-half? 0
    * set color cyan
- end ask districts

All districts choose-use-own-ratio

- ask districts
  - ifelse best-district? = 1
    * set use-own-ratio? 1
  - else
    * ifelse “bottom-half? = 1” and “water-quantity-per-person >= target-quantity”
      · set use-own-ratio? 1
    * else
      · set use-own-ratio? 0
      · set color red
- end ask districts

Meme replication procedures All districts replicate-meme

- Ifelse “use-own-ratio = 1”
  - Set planned-X (actual-X)
  - Set planned-Y (actual-Y)
  - Set planned-Z (actual-Z)
- Else
  - If “replication-method = fully-rational”
    * Set planned-X (actual-X of districts with [best-district? = 1])
    * Set planned-Y (actual-Y of districts with [best-district? = 1])
    * Set planned-Z (actual-Z of districts with [best-district? = 1])
  - End if
  - If “replication-method = myopic”
    * Ask TSUs
      · Set x item 0 [actual-X] of myDistrictList with [best-district? = 1]

        - Set y item 0 [actual-Y] of myDistrictList with [best-district? = 1]
        - Set z item 0 [actual-Z] of myDistrictList with [best-district? = 1]
      - Set planned-X x
      - Set planned-Y y
      - Set planned-Z z
    - If “replication-method = random”
      - Let n (one of districts)
      - Set planned-X (actual-X of district n)
      - Set planned-Y (actual-Y of district n)
      - Set planned-Z (actual-Z of district n)

Meme variation procedures All districts variate-meme

- If use-own-ratio? = 0
  - If variation-method = “random fractional”
    - Ifelse replication-method = “random”
      - Do nothing
    - else
      - Let xx (actual-X − planned-X)
      - Let p (random xx + 1)
      - Let newx (actual-X − p)
      - Let newy (actual-Y + p)
      - If “newy > 13” [Newy = 13]
      - let newz (100 − newx − newy)
      - set planned-X (newx)
      - set planned-Y (newy)
      - set planned-z (newz)

Grow district population All districts

- Set population int (population + (population * population growth rate)

Water points age and fail All WPs

- Ifelse “operation-state = 1”
  - Set age age + 1
  - If “age >= expected-lifetime”
    - Set operation-state 0
    - Set color red
    - Set non-functioningYears 0
- Else
  - Set nonfunctioningYears NonfunctioningYears + 1
  - If nonfunctioningYears = 5 [die]

Calculate capex and capmanex budget All districts

- Set capex-budget planned-X * DCG
- Set capmanex-budget planned-Y * DCG

Spend capex Repeat over the number of districts

- Set maxNewWP int capex-budget / capex-price
- Set capex-spent maxNewWP * capex-price
- Create WPs maxNewWP
  - Set district-number to corresponding district
  - Set TSU colour to corresponding TSU
  - Move-to one-of patches with [pcolor = TSU-colour]
  - Set shape and size
  - Set color blue
  - Set age 0
  - Set expected-lifetime int random-normal 6 1.5
  - Set operation-state 1
  - Set nonfunctioningYears 0
- End create WPs

End repeat

Transfer residual capex All districts

- Set capmanex-budget capmanex-budget + (capex-budget – capex-spent)

Spend capmanex All districts

- Set maxMaintenanceWP int (capmanex-budget / capmanex-price)
- Count non-operational WP: count myWPList with [operation-state = 0]
- Ifelse maxMaintenceWP > count non-operational WP
  - Ask myWPList
    - Set operation-state 1
    - Set color blue
    - Set nonFunctioningYears 0
    - Set age 0
    - Set expected-lifetime random-normal 6 1.5
  - Set capmanex-spent non-operationalWP * capmanex-price
- Else
  - Ask n-of maxMaintenanceWP myWPList with [operation-state = 0]

    * Set operation-state 1
    * Set color blue
    * Set nonFunctioningYears 0
    * Set age 0
    * Set expected-lifetime random-normal 6 1.5
  - Set capmanex-spent maxMaintenanceWP * capmanex-price

Update WPList and functionality percentage All districts

- Set myWPList turtle-set WPs with [district-number = number]
- Set functionality-percentage (count myWPList with [operation-state = 0]) / (count myWPList)

B | Interview Report: Conceptualisation phase

Date:	March 31th, 2016
Location:	IRC Headquarters, The Hague
Interviewer(s):	Felix Knipschild, Deirdre Casella
Interviewee(s):	Jane Nabunnya Mulumba, Country Director IRC Uganda
	Alana Potter, IRC Africa Regional Manager
	Martin Watsisi, RegionalWASH Advisor IRC Uganda

Content Interview In general, we spoke about the relation of the thesis work to the ongoing research in Uganda, the use of modelling and the use of learning in delivering systemic change, the conditions that enable or disable learning, the application of learning to the financial allocation case, a successful case of learning with the formation of the HPMA and about follow-up contacts in the sector.

Systemic Change *Alana*: If you talk about systemic change, there is a bunch of theories you can talk about: finance, planning, constellation of institutions. You will affect some sort of systemic change. There are twelve or so things that affects systemic change. We know that if you change different pieces of that stuff, you can change something in the system. Exactly as Martin said, if you put more money in, you put more engineers in, this happens. What you are saying is how learning can contribute to systemic change. Learning does affects systemic change, but it is just one thing. And you are willing to answer that *how*. Is it because it is learning about any of those? Or does the tool not necessarily help people on how to spent their resources, but more a tool for increased insight or understanding on how they can create systemic change.

Felix: If it would be a tool, then it'd be a tool for us to understand how learning contributes to delivering systemic change. And how we can stimulate those things in learning that contribute to delivering that change. Why then learning? It is because you can learn about each and every one of those aspects and how to apply them. If you can learn about learning and understand what in learning contributes to delivering the change you want, then you can apply that to any case.

Deirdre: Your starting question was What system? At the Faculty we work we speak a lot about Socio-Technical Systems. These are systems where social interactions make decisions about technical artefacts, bounded by all kind of things like rules, laws and culture. We are aware that such a system is not complete, that is resides within another system, within another system.

Alana: The biggest learning was that the rural water sector is not a system in isolation. This is just a caveat.

Deirdre: We zoomed in on rural water. Rural water was most of the research done in the Triple-S programme, which is the basis of this research. Programmes such as WASHcosts surpassed this programme with research on sanitation and hygiene.

Alana: Sanitation shows just really nice potential as it is so much about behavioural change. Makes is so much more complex.

Martin: The learning and the changes in the system are there. It's the consciousness and the conscious intentions, that is what we would wish to see in this model.

How is learning observed in the sector? *Felix*: What I want to achieve is seeing if modelling in such a system, or in a part of such a system, makes sense for research in the sector and for stimulating learning in practice. And therefore I pick a really tiny part of the rural water supply sector, as that is how I think I can manage within my research that I can contribute.

Alana: How do people learn? I think very little is about what they read, a lot is about what problems that they saw and the people that they talked to. They lived an experience. They learn from each other, they learn from experience, they learn from bad experience often more than they do from good experiences, because they have a lot more motivation. Anything that makes you optimally uncomfortable will make you learn. The way you read a written text is the tiny little piece of the individual learning. It's largely from each other, from experience, from life, from conversations, from having you in challenging situations, from the friends that we form, from problems that we have never considered before. It needs to be optimally uncomfortable, if it's too uncomfortable you block because you are frightened. And if it's too comfortable, you have no motivation. So on that continuum from comfortable to super uncomfortable only the middle provides an opportunity for learning. How that happens there: optimal challenge, optimal opportunity, optimal ability to analyse and pull out and then generalise to different things. It's the questions we ask rather than the answers we are given. Creating opportunities for learning, creating a space that fosters learning is something that... why would you make adaptive choices if there is nothing to adapt to? No one wants change. And maybe if you learn something new, it forces you to change. If we'd learn that the earth is flat, we might be forced to change to change some of our behaviours.

Introduction to Case What would we take then as an example that we can crack our heads over. A good example where the system had to learn. We took the district conditional grant formula in Uganda. There is a 30%-70% allocation split. However this had a countervailing effect.

Martin: The DCG is there to determine how much district X gets per year for water service. From that amount 70% had to be spend on new infrastructure, 9% on administration, 11% Operation & maintenance, etc. So not only CapManEx.

Felix: The power to change the allocation ratio changed from national level to district level. That just happened late 2015. However we haven't seen documentation of it. This allows the decision to be made closer to the place where the service is actually delivered.

Alana: That's exactly what we would argue for, allocate some resources other than to new infrastructure and to get closer to the level that they are delivered.

Deirdre: We see this as an example of learning. Learning across institutional levels: information on the ground found its way up to national level that decided to change a policy.

Alana: Be aware that it is an assumption that learning took place in this case. It depends where the actual decision was made. Was the decision made in learning is the big question. Maybe it was simply based on a policy or something coming down the pipe that has nothing to do with learning. May or may not have.

Furthermore, it makes governments look so much better when they build new facilities then when they put money into keeping things in existence. I build 20 boreholes gets you more votes than I rehabilitated 20. There is this whole notion of political power and these situation are not so much about learning but about posturing (impressing / misleading): Position or power, or status, or the way you look. There is a very nice tension between learning and power. Some say, knowledge is power, but sometimes power is to turn knowledge down. To maintain power means to shut knowledge down.

Have a look at the experiential learning cycle. It's helpful in this case.

If you can change the mindset of government, if you can change the focus from delivering a borehole to delivering a service, then you change the whole terrain.

Stakeholder specific questions *Who was most important in contributing to the decision to change the decision power in the allocation formula?*

[an explanation of the allocation case.] The district is the level that collects the evidence. In Triple-S we helped raise that voice, we helped the to bring up the evidence to the national level. The decision is made at the national level. The district can provide evidence that things are not working as they should, but they cannot take the decision. This means someone at the national level should be able to see the evidence on the ground, at the district level. A policy or regulation at the national level can change that.

The District Water Officer is the focal person for water and sanitation. As an individual is quite small. The good thing is they have an aggregated forum: the District Water Officers Meeting every year. Now evidence from 1 district is aggregated for 111 districts. At the district level, Civil Society Organisations, are frustrated as well. There is too little money for direct support and there is evidence.

Regional level is a few districts. Kabarole is a district. It is in several regions. In Rhwenzori region. There is a Rhwenzori WASH alliance, we have a Rhwenzori region learning alliance. The Ministry also has Technical Support Units. These are the ministries agents. The country is divided in 8 TSU's. It is a conditional grant, district can implement it according to the conditions. The TSU focus on the implementation, how do you implement the DCG? They are they eyes of central Government on this. I would take these as very key actors. TSU is government. If there is any change, probably the DWO can bring it to the TSU and aggregated bring it to the national level for a decision.

At the national level: the TSU is coordinated by the rural water department. There is a commissioner that speaks to the Directorate of (rural) Water and Development. The department is within the directorate. The commissioner is the commissioner of the department.

Learning for us is behind the scenes, for a CSO (Civil Society Organisation), you can only knock and push people forward. Make suggestions, request things. Eventually, government can listen. So if you talk about how this kind of learning is happening: how are the behaviours changing? Is it direct interventions, bring new knowledge on the table, this is what we think works? Or is it the 'behind the scenes'. CSO's have learned that the government can be influenced somehow. From behind. To change what they are doing. If you take a direct confrontation: this is not good. The government is scared to be taken out of its positions of control. The best is to help them to let them move the things.

Conclusion on stakeholders to look into (via e.g. DIM):

- *Director of DWD (national)*
- *TSU (regional)*
- *DWOM (inter-district)*
- *DWO (district)*
- *Rhwenzori learning alliance (regional)*
- *Rhwenzori WASH alliance (regional)*

The change of power to district level is not what happened. It is the allocation formula that decides how much money a district gets that is recently changed. The power resides at national level. More info is on the Ministry website and in the DIM. There is a background document on the revision of the DWSCG on the website of the MWE.

Hand Pump Mechanics case Martin: Maybe this wasn't the best case to demonstrate learning. The case of the Hand Pump Mechanics is even a better example of learning. Why? The associations are a bit started by some NGO's in northern and western Uganda. Through regional learning forums recognition of the role they can play in O&M is raised. The awareness is raised. It spread from 1 district, to 3, to 5, to 15 to many. The case is brought from the regional learning to the national learning. It's documented, it's presented. Government takes it as an undertaking. A best practice. Every year in the SPR they write 1-3 best of practice. It gets documented. When documented in SPR (2010), after that they formulated an agenda for implementation in the next year. They pick it up and say we are going to implement it in 70% of the districts and start implementation in 30% of the districts. Then it becomes an undertaking. From the Sector Performance Review Meeting (sept/okt), they formulate these undertakings. It is an agenda for the next years implementation.

This is a better case, because it shows how through learning the good practice of having the associations at district level was raised from the district to the regions to the national level. Eventually it became an undertaking. An after that it became a common practice. And now every district has an association.

There is a briefing note on HPMA on how it happened. There is information on the Rhwenzori learning alliance. You can read guidelines on engagement of the HPMA on the government websites.

C | Interview Reports: Validation Phase

Validation of the implementation and observed behaviour in the ABM is done through *companion modelling* throughout the process and by a series of four interviews after the construction of the ABM and the preliminary analysis of the results of the experiments. All interviews have the same set-up. The interviewer describes the implementation of the ABM by systematically showing and discussion the assumptions made in the conceptualisation phase. The interviewee is asked to reflect on the assumptions based on their experience and expertise.

In the second part of the interview the process is repeated for the insights generated by the results of the experiment. In the validation of the behaviour of the model the interviewer(s) and interviewee reflect on the model behaviour. This is done through showing the general model behaviour, the different scenarios for replication and variation and the insights generated by the experiments with loosened restrictions in the allocation ratio.

Though the interviews are set-up in a similar way, the focus of the interviews varies between the first and the second part. This is caused by the expertise of the interviewee.

C.1 Expert Validation Interview 1

Date:	June 17th, 2016
Location:	Faculty of Technology, Policy and Management. Delft University of Technology
Interviewer(s):	Felix Knipschild
Interviewee(s):	Abby Onencan, PhD candidate Sustainable Nile River Basin Management, Faculty of Technology, Policy and Management. Delft University of Technology

C.1.1 Validation of Model Assumptions

Multi-Level Governance There are more lines of communications in the representation of the system, there is information from regional going down, from district directly going up to national level. Actually, every line has both arrows. The information lines are not clear, a bit more messy. Most of the information spread is not bottom-up, but it is top-down. With a decentralised system you need to have a very strong information system to learn what is going on 'on the ground'. National level is actually not learning themselves, as top down decisions are made without knowing what is going on in the districts. It is also a capacity problem. If you decentralise in a multi-level governance system you have to realise you have to build capacity at all levels.

Regional level is not a 'solid' or 'tangible' level, compared to national and district. In terms of a governance level it is a shaky level in Uganda. The level is questionable in terms of authority. There are multiple interpretations of a region, and there is a struggle between river basins and regions. There are more levels of governance as you identified.

District representation You assume that districts are the same. They are also different in terms of organisation. Districts can for instance have different goals, e.g. optimising and earning money from the water supply system versus a conservative approach, where the district authorities try to serve everyone in the district.

Water Infrastructure People also get their water from fresh water sources, like rivers and lakes. A good assumption to mention is that there is no complexity in how and at what moment districts break down. It is all peered down to a normal distribution. The collection of funds for minor maintenance is considered in the normal distribution.

District Water and Sanitation Conditional Grant Most of the districts don't want to report above the national average. They get punished for performing well. Why do certain districts perform well? Fresh water, good governance? Worth some investigation. Do district that want to earn money, make economics out of water: that would change the whole dynamics. Furthermore, be aware that the DCG is not the only source of money.

Investment Strategy Districts Districts are reactive in maintenance. They do not do regular maintenance every year. So observe the budget as a budget reserved for maintenance events during the coming year.

Selection of good and bad policies You are assuming that the definition of good and bad is correct. Otherwise districts are learning the wrong things. The ranking system is not used in Uganda. It is used in South-Africa. No rankings are made in Uganda.

C.1.2 Reflection on Model Behaviour

General System behaviour Steep decline can be caused by 1) interpretation of WSL is different than coverage, 2) data in the water atlas can be flawed. Yes, I can see that as they want to provide a good picture of the current situation.

Replication method Some district just don't want to learn. They just continue to do the same over years. They are too busy with their policies. It is the more natural way of learning though. Furthermore, fully rational seems to be too much top down, as districts are not the same, so not every good policy would work for every district. The myopic seems good as long as regions also can learn from each other. Otherwise the learning is restricted to the districts in the region. I can imagine that in practice the districts from different regions learn from each other.

They all have their positives and their negatives, so I would say that at the end of the day you would want to have a mix of the three. I cannot really tell which one would be more effective.

Loosened restrictions in the Allocation Ratio This actually represent a situation where we transfer the mandate to decide on the ratio completely to the district level.

C.2 Expert Validation Interview 2

Date:	June 17th, 2016
Location:	IRC Headquarters, The Hague
Interviewer(s):	Felix Knipschild, Deirdre Casella
Interviewee(s):	Patrick Moriarty, Chief Executive Officer IRC

C.2.1 Validation of Model Assumptions

Water infrastructure The normal distribution seems reasonable to represent the water point breakdown seems reasonable. The assumption of abandonment of water infrastructure after being non-functional for 5 years seems right as well.

C.2.2 Validation of Model Behaviour

General System Behaviour The question what I think the system will behave like is difficult to answer, because I don't know the amount of money going in and I expect the system to be money-driven. So if you have used a realistic amount, I expect it to be going down. After 5 years, the system stabilises. This means they are putting enough money in to keep the system stable, which I didn't expect, I expected the levels to go down.

But why are the starting levels so high? You start at 95% and they don't put enough money in to remain at that level. What would happen if you pull your starting assumptions down? It be interesting to see what happens if you put more money in? What drives the system to stabilise at 14? I suspect it is money and learning will help a bit, but it is money that drives the system.

Initial state: These numbers are based on the real system, on data from Uganda. So it should be good. When aggregated at the district level, coverage is actually about 95%. Initial state is observed fact. In Uganda they do calculate in different ways: there is a discrepancy between how people measure the coverage: national level – there are 500 people, 1 borehole, so 200 people are not served, coverage of 60% - whereas district level – we get water from a hand pump, all served.

It can also be that the steady state should be at the level of your starting point. Than the assumptions in the model about for instance prices and lifetimes can be / are wrong. I am still convinced the system is driven by money. Moving on from the starting point: water infrastructure breaks down and investments are made. Since the performance is going down, more infrastructure breaks down than is repaired or constructed, until it reaches a stable state where enough infrastructure investments are made to keep up with the failure.

Another cause of the high initial conditions is that there has been a big infusion of money to get to the initial level. As you are only relying on the DCG you leave out money from donors. Are you right about the assumptions about investment prices etcetera. They got at 19 not only because of the DCG, but also projects, donors, other sources.

Replication method I expect to see fully rational on the upper part of the distribution, myopic at the bottom and random all over the place. In reflection on the results: fully rational gives the biggest spread. So you should go for myopic or random.. they perform marginally less well, but they give less spread.

They are not generating a huge difference; 14.5 to 18.5 or something. Again, if you cut the money off, every run will go to zero. The money is a threshold criteria.

Variation method I expect a slight difference, room for manoeuvre in policy is not that big. Be aware of a confirmation bias: we see what we wanted and expected to see. If you defined what a good policy is, and they copy a good ratio from each other, why would random ever work better?

Loosened restriction Allocation Ratio So what you can say here: ignore what Ugandans are saying about access. You are more or less at full access at the starting point. If you force people to spend 80% of their money on new infrastructure, even if they already reached their target, and therefore are starving the existing systems of investment, you are going to run them down. If you accept that you've already achieved a 100% coverage and therefore you put all your money into maintaining that, you actually raise the service level.

This is great, I really liked the conceptualisation of learning and that will help IRC. You distilled it down to what it is about. Your results say, yeah learning may help a bit, given that you have enough money and not a stupid policy that informs you to do the wrong thing. What I like is that you've set it up to follow the policy. This big insight came after you, completely honest, modelled the system the way it works. And then you found out, if you take those restrictions away, you could do a whole lot better. You did not set out to do basic financial modelling, but essentially you have. Learning just created noise and made it look realistic. Learning is driving investment decision in your model and it shows that investment decisions matter a lot. A lesson here: let the district themselves decide how to spend the money.

Limitations of the approach: by choosing aggregation on district level, you miss all the granularity in what drives the district to make the decision. Their policy making is not being driven by looking at an aggregated system. They have a rule based system where they try to serve the unserved communities. They do not look at aggregated levels. Your model shows: with the money that you are putting into the system, you can actually maintain the level that you have and even slightly improve the level, but the policies are wrong.

C.3 Expert Validation Interview 3

Date:	July 15th, 2016
Location:	Faculty of Technology, Policy and Management, Delft University of Technology / Kampala, Uganda
Interviewer(s):	Felix Knipschild
Interviewee(s):	Martin Watsisi, Regional WASH Advisor, IRC Uganda

Multi-Level Governance in Uganda First we discussed the multi-level governance situation in Uganda. A few things are worth noticing here. In addition to the information in Figure 3.1 the different institutional levels in general play a different role. The national level, the level of the ministries, has the role of a regulator. The regional subsequently is often seen as an intermediate. One that communicates between the national level and lower levels. The district level serves as a service authority. Furthermore it is important to describe some dynamics between the district level and the lower institutional levels that are merged into the district level in the ABM. Whereas District Local Government serves as a service authority, all kinds of service providers circle around this office. These are the parties that work for the district local government and implement the services. These service providers are for instance water boards at sub-county level, contractors and hand pump mechanics. The District Local Governments are the authority at district level, but they always need other parties to execute the projects.

Continuing on the District Local Governments: the Chief Administrative Officer (CAO) and the District Water Officer (DWO) are both part of the DLG. The CAO has more tasks related to the political aspects that concern the DLG, whereas the DWO is concerned with the technical details of the efforts surrounding water supply. The CAO is higher than the DWO in terms of hierarchy within the DLG.

Representation of Regional level Second, the discussion merged into the presence and authority of the regional level. Martin recognised the learning venues at regional level. A good example of such a venue is the Rhwenzori WASH alliance. In this alliance specific attention goes out to collaboration and learning between District Local Governments. Furthermore there is one other important venue: the Inter-District Meetings. Worth noting is that these meetings are organised by the Technical Support Unit (TSU). The regional learning that is represented in the myopic replication method looks most like an Inter-District Meeting, as districts within a TSU region come together at this venue and share with each other.

The role of the TSU as it it used in the fully rational replication method, representing a national structure and cycle of learning is clearly based on the case of the foundation of the Hand Pump Mechanics Association (HPMA). In this case a HPMA was piloted in one district. Since it was successful the pilot was scaled up to four other districts. After this the Ministry of Water and Environment constructed an undertaking where the goal was to spread the HPMA to at least 80% of the districts.

Furthermore, considering the learning cycles, Martin mentioned that the process of districts sharing with each other is a very slow process. It has to do with trusting each other and with opening up to new ideas. The time scale of a regional learning venue to work properly for instance is very long.

Geographical homogeneity districts and DCG Third we discussed the assumption about the geographical differences between the districts (3) in relation to the yearly budget the districts receive (9). The geographical characteristics in a district, as Martin stated, enable different types of water infrastructure and can make the construction or maintenance tasks more or less expensive. Imagine constructing a water point in an area that is hard to reach and far from a city compared to one on flat terrain, close to a city. The budget that the districts receive includes these types of considerations. A district that is more rural and where implementation of water services is more expensive receives a larger budget from the government. This results in a slight misrepresentation in the ABM: the districts in the ABM receive the budget that the actual districts receive, but the prices for infrastructure are similar for all. This might cause that some districts perform better than they in practice would.

In reflection: an assumption that is not mentioned explicitly in the thesis is the assumptions that all districts have the same Average District Per Capita Costs (ADPCC) of water services. In districts where the implementation is harder, the ADPCC would be higher. This would have been a way to implement this factor in the ABM.

Performance Indicators Fourth, we discussed the representation of performance indicators in the ABM. Martin stated that in Uganda they do not measure how much water every person gets, as is done in the ABM. In Uganda they measure if a person is able to access. They draw a line of a kilometre around a water point and every one within that area is served. This is how the coverage number is measured. We also name it access: what is the percentage of people with access in that area? It is not measured how much everyone then can access, so what you measure is not measured in Uganda. Therefore it is not easy to compare.

C.4 Expert Validation Interview 4

Date:	July 27th, 2016
Location:	UNESCO-IHE, Delft
Interviewer(s):	Felix Knipschild
Interviewee(s):	Yared Abebe, PhD candidate Urban Water Systems, UNESCO-IHE, Delft

Reflection on Assumptions about Ugandan System The assumption (3) that districts are similar in terms of geographical characteristics seems like a fair assumption. The only characteristic that you leave out is the possibilities for different water infrastructure, e.g. the source of the water (river, ground water). An option to represent districts with 'lesser' conditions (rough terrain, deeper ground water) is to give them limited resources in the simulations. On a first glance it seems that you can cover all that you loose in the assumption with such an addition. However, you do not have the topography represented in the model. District can have flat or rough terrain, resulting in different opportunities for infrastructure, such as the efforts needed to pump the water up. It would have been more important in the case of piped schemes, as we now conclude that another assumption is that all infrastructure is a shallow well with a hand pump. However, all in all, it seems like a fair assumption. Taken into account assumption 4 about the single type of water infrastructure, you don't need the terrain. It does not affect the model so much. It mainly matters for the water resource.

In that light, considering the assumption (6) of breakdown of the wells, you need to consider the causes and the severity of a breakdown. A breakdown that can be caused by a variety of things and in the model this is all represented in a single distribution. This makes the assumption for the 6 years in the distribution very important for the behaviour of the model. The assumption is based on one of the other experts and ideally you would have data to support this claim. Another reflection to make is that a shallow well might also malfunction, because the ground water level is too low. A simple replacement or repair won't fix such a water point. It would need ground water resource management and a number of other interventions, not only limited to technical solutions.

What follows is a discussion about the use and implementation of the allocation ratio and the way the budget is transferred to the districts. This discussion is based on assumptions 8 and 9. First of all the budget in the District Conditional Grant is only meant for investments in WASH. In the ABM this is further abstracted to investments in water supply. For other purposes, such as education or health care, the districts have and receive other budgets from different ministries. Though these are all out of the scope of the research, it is important to mention this explicitly.

Regarding the formula that national government uses to decide the amount of budget a district receives there is one other mechanism that is observed in practice, but not present in the ABM. In a case of financial allocation it is not desirable for a district to deliver worse than their projections. There is a negative connotation with under-performance. Also, not spending all your budget can in practice lead to a lower allocation in the next year. These two dynamics are not represented in the ABM. The implementation of the formula is done in a stable way, because the available description of the formula that is used in Uganda is not comprehensive enough.

In a discussion about the goal of the formula as formulated by the Ugandan national government we discussed how the policy itself should evolve. In the current implementation the policy is designed to stimulate particularly those areas that perform below national average. What would happen if all district perform *average*? There are no threshold values or follow up policies that show how the policy will evolve when certain goals are met. This institutional dynamics of developing goals and policies to support them is absent in the formula and, hence, absent in the ABM.

In retrospect to assumption 10 - assuming the investment strategy of the districts - some sanity checks can still be done. You can imagine that there is a maximum number of wells within a district that is still sane. This can tell something about the validity of the assumptions for the price of CapEx and CapManEx and for the budgets the districts receive, as well as for the assumptions about the lifetime of the water infrastructure.

Furthermore, in retrospect to the discussion about the negative connotation with unspent budget, you need to consider where the money goes when it there is not enough budget for a complete CapEx event. The transferring of the budget to firstly CapManEx and after that unspent budget seems like a fair assumption, though in practice the budget is spent on a project base.

Reflection on Assumptions about Implementation of Learning First of all we named explicitly that means of communication matter in the spread of a policy through a system. This is represented in for instance the difference between inter-district learning - one district calls or meets another - and the national learning structure - a policy becomes mandatory by means of a law or undertaking. The bigger the reach of your communication tool, the higher the spread of the meme.

In reflection on assumption 12 - stating that districts have full information about the state of the infrastructure - Yared responded that this is actually the case. Maybe it is not on a district level, but when infrastructure stops to work people will complain and report. Maybe there is no paper trail with an official report, but there is reporting when water points break down. This makes the assumption closer to the real behaviour as originally thought.

In the replication process, the ABM represent a situation where the districts evaluate themselves. They scan their environment under three different conditions for vision, and they evaluate their performance based on the other districts. In the ABM the environment evaluates by constructing the ranking, but in practice it is mainly the districts themselves that evaluate.

In the variation process you have to reflect on the formula that is used in the *random fractional* implementation. What is the scientific background for the use of that formula? It can change both the ratio for CapEx and the ratio for CapManEx, which is not clear from the figure that represents the step. Clearly state what the step and the formula represent: is it a budget consideration? Is it an error in communication? Next, you have to state how your implementation exactly represents these considerations.

The geographical implementation of Uganda in an ABM is not difficult. You can represent the actual Uganda if you can support it with GPS data or a GIS framework. This will help in the communication with the Ugandan stakeholders in the project.

Reflection on Model Behaviour The model behaviour shows a big drop in the first five years, more or less one cycle of infrastructure, and then stabilises. In the different methods for replication we can see great differences. A possible explanation for the greater spread of the fully rational replication method is that a policy is spread quicker and therefore the system might be more sensitive to the starting conditions of the ratio which are assigned randomly. A method to verify this statement is to, intentionally, set the initial allocation ratio to *good* or *bad* and verify if indeed the system behaves more sensitive to the initial conditions.

Furthermore on the replication method, we can see that the median of the fully rational method is higher than the myopic method which in turn is higher than the random method. The spread, however, grows in the opposite direction. From the figures that support this claim we can also see that outliers can be really good, but also really bad in the fully rational method. This is where a policy maker should make his decision about. What do we prefer?

A similar discussion is possible on the outcomes of the variation step. What you can conclude is that the random fractional method actually performs better: the median is similar to the perfect copy method but the spread is less, i.e. there are no really bad cases. This is what Ugandan government is currently aiming for with their water supply policies represented by the formula that decides how much budget a district receives.

While discussing the implications of the model simulations with the loosened restrictions we came to the point that it is a moral discussion. There are different performance indicators: water quantity per person versus coverage. Based on a preference for a performance indicator you can reach different conclusions. Will you invest the budget in such a way that there is more water produced, ignoring the geographical distribution of the water? Or will you invest your budget in such a way that most people have access to water? And do the two exclude each other? This research can give Ugandan policy makers the handles to start such a discussion.