

Social learning & systemic change in Uganda's rural water service delivery: an environmental study on the effects of social learning in water resource management

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Preface

This graduation thesis marks the end of my journey as a master of Industrial Ecology student at Leiden University and TU Delft. I'm satisfied with the outcome of this thesis. As this was my first thesis research project and I was able to work through unfamiliar concepts and processes to finish the project; I would like to take a moment to thank those who have supported me along the way to make this thesis project possible.

I would like to thank the members of my graduation committee: Igor Nikolic, Deirdre Casella, and Jill Slinger for all the expertise, extensive feedback, patience, and guidance you all have given me throughout the entire thesis process. I would like to especially thank Deirdre for sharing your professional network with me. I also wish to thank Angela Huston for taking the time to provide feedback on the project as well.

To my mother and father, I would like to thank you for your love, understanding, and unwavering support.

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Swayon Leung Wai Yeung

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Executive Summary

In the Republic of Uganda, the rural water service delivery infrastructure heavily depends on GW resources. The demand for GW is expected to increase in the future as only about 65% of the population have access to improved sources of water. GW scarcity was argued to be a sustainability problem for the environment and water security in Uganda; because there is no GW recharge in the aquifers according to the database from the United Nations. A recent discussion in Uganda's water, sanitation and hygiene (WASH) sector, suggested the ability for the sector as whole to learn and adapt could influence the ability to overcome current and future challenges. Social learning is a form of sector learning which is commonized in Uganda's WASH sector and researched for water resource management in a different context. Hence, the focus of the research was to explore social learning for GW management in Uganda's rural water supply. Agent based modelling is a method to explore within the focus of this research; through replicating concepts, actions, relations or mechanisms that are proposed to exist in the reality, in silico for observation. This led to the following research question for this thesis: *How can social learning be conceptualized and modelled for GW rationing in Uganda's rural domestic water service delivery?*

Prior to modelling, three key components were conceptualized. Social learning was conceptualized using memetics, selection, variation and replication based on Knipschild (2016). The rural water supply delivery landscape was conceptualized using the socio-technical system perspective and multi-level governance. The exclusion of the environmental dimension in the socio-technical system perspective was addressed through conceptualizing GW a constraint within the technical dimension of the conceptualized system. GW rationing was argued to be possible under the multi-level governance perspective in Uganda and was conceptualized to restrict the amount of water allowed for withdrawal at a hand-pump water point by calculating the expected amount of users. Simplification of the conceptualizations and assumptions were needed to translate the above mentioned conceptualizations into a agent-based model.

The designed model was applied to a case study in Uganda and domain experts were consulted to ensure the conceptualizations used in the model and the outcomes of the case study were suitable to the study and reflect reality. Under the influence of social learning, multiple patterns about GW levels and water service levels emerged from the application of the model. As population growth rate and water point growth rate increase independently or concurrently, GW depletion rates increased due to the assumptions made in the design of the model. GW performance increased as ration ratios decreased and GW performance was influenced by different social learning styles as a result of ration ratio knowledge exchanges. Network connectedness theory was used to suggest why GW performances were influenced by the different social styles and the exchanges of ration ratios. Highly connected and steady learning networks performed the best from the case study, because the diffusion and accessibility of high quality memes was possible within the above mentioned network structure. The importance was network connectedness over steadiness was suggested from the case study through the different social learning styles for Uganda's rural water supply delivery under GW rationing. Ration ratios were approaching zero over time in the simulation leading to undesired water service levels for water users as well. The model results showed a

large amount of water users needed to travel long distances to collect enough water for domestic use; and a large amount of water users contained a water collection portfolio of less than 10% water from improved sources as a result of rationing. Despite the simplifications and assumptions made for the designed model, the designed model, conceptualizations, assumptions and findings from the case study suggested behaviours under critical situations in reality. Under non-critical situations, decision making and learning of ration ratios includes water service levels performance and other factors beside GW performance. The model results also suggested rationing from an informal perspective where rationing is in place without regulations.

In conclusion, GW depletion rates can be reduced through social learning and rationing. The application of social learning under the preferred network structure can increase the sustainability of GW resources and water security. However, when the intensity of rationing is determined only through the consideration of GW performance, undesired water service level can surface as water users are required to travel further distance to collect enough water and forced to use alternative water sources such as an unsafe source. Complex environmental dynamics can be avoid at the cost of increased uncertainty, when information about the environmental dimension is limited to conceptualize the dynamics of the rural water services in Uganda through including a constraint within the technical dimension of a socio-technical system. Environmental strategies can be diffused or emerged through social learning to address other sustainability related issues where the application of (new and innovative) technical solutions is limited; however, environmentally focused strategies can lead to detrimental effects in other areas in reality and should be taken into account when strategizing for the environment to ensure sustainability in the area of interest.

Recommendations for Uganda's rural water services were made based on the findings of this study. Since Uganda's rural water service delivery infrastructure is heavily depended on GW resources, diversifying the infrastructure and creating awareness of the problem of GW depletion was recommended. Rainwater is an abundant renewable water source in Uganda and the diffusion of rainwater harvesting and storage technologies was suggested. The setup of a highly connected and steady learning network through the creation of an association for GW management was also suggested. This way learning for GW management can be standardized and regulated to increase the performance of resource management as local solutions can be diffused as well along with the solutions made from the national level.

Future research should focus on further improving the designed model through researching the simplified or excluded components, validation of findings through applying the designed model to a different case study or increasing the amount of experimental repetitions and continue exploring the effect of social learning when applied to resource management and rural water service quality in Uganda.

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List of abbreviations

ABM - Agent based modelling
BF - Sustainability factor
CAS - Complex adaptive system
CBM - Community-based management
CDT - Classical decision theory
DLAs - District level authorities
DWRM - Directorate of Water Resources Management
EQ - Experiment question
FAO - Food and Agricultural Organization of the United Nations
FR - Fully rational
GW - Groundwater
GWL - Groundwater levels
LCT - Life cycle thinking
lpcd - Litres per capita per day
MLG - Multi-level governance
MWE - Ministry of Water and Environment
PopG - Population growth rate
RQ - Main Research question
RWH - Rainwater harvesting
RWSD - Rural water service delivery
SDS - System dynamics simulation
SES - Social-ecological systems
SF - Safety factor
SGS - Serious games simulation
SGW - Renewable GW
SL - Social learning
SRQ - Sub-research question
STS - Socio-technical system
TOFR - Total outflows from recharge
t-SNE - t-distributed stochastic Network Embedding
TR - Total GW recharge
WASH - Water, sanitation and hygiene
WPs - Water points
WPG - WP growth rate
WSL - Water service levels
WU - Water user

1. Introduction

The following document is a thesis project report for student W.Y.S.Leung's graduation research project for the master program of Industrial Ecology. In this chapter, background information regarding the rural water service delivery (RWSD) situation in Uganda will be introduced in section 1.1, followed by an explanation of the problem in section 1.2. Project description, research questions and the scope of the thesis project derived from section 1.2 will be introduced in section 1.3. A description of the thesis project report structure will be given in section 1.4 at the end of this chapter in preparation for the reader in the chapters ahead.

1.1 Rural water service delivery (RWSD) situation in Uganda

One of the sustainable development goals set by the United Nations was to ensure all humans on earth get access to safe and affordable drinking water by 2030 (United Nations, 2017). However, an estimation of about 32% of the rural population in Uganda does not have access to safe water and an estimated 15% of the water points (WPs) installed in the rural area does not function properly to allow citizens to draw safe water from (Knipschild, 2016). This equates to an estimated population of 9 million Ugandans without access to safe water (Nimanya, Nabunnya, Kyeyune & Heijnen, 2011).

Currently in the rural areas of Uganda, groundwater (GW) is one of the major sources for domestic water supply as shown in Figure 1 (Nsubuga, Namutebi & Nsubuga-Ssenfuma, 2014). Deep boreholes, shallow wells and protected springs are the main methods for GW supply (Nsubuga, Namutebi & Nsubuga-Ssenfuma, 2014). The majority of the WPs apply these above mentioned methods and are equipped with hand pumps to gain access to GW for domestic purposes. These hand pumps malfunction over time and restrict safe water access for Ugandans. Furthermore, the malfunctioned WPs often either require an extended period of time to get repaired due to financial and technical issues which delay accessibility or may end up abandoned (van Tongeren, 2014).

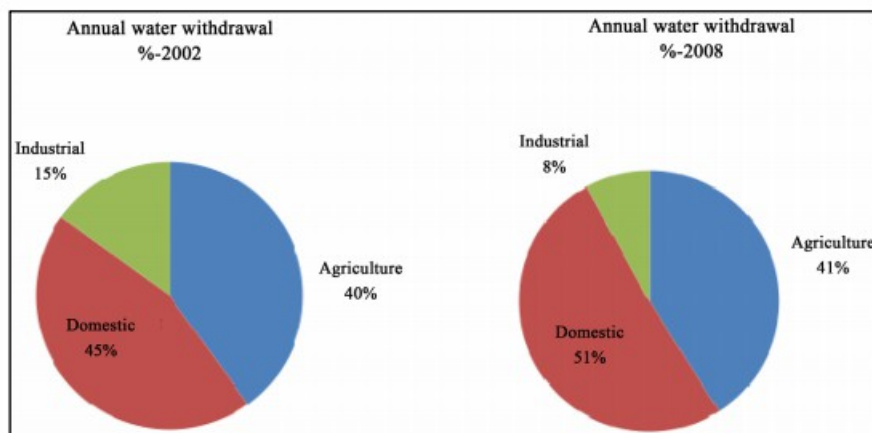


Figure 5. Water withdrawals in Uganda. (Data was sourced from WRMD quarterly reports, joint water sanitation sector program support, DWRM).

Figure 1: GW withdrawals in Uganda (Nsubuga, Namutebi & Nsubuga-Ssenfuma, 2014)

Efforts were made by the Ugandan government, research community and other actors to address these issues (Knipschild, 2016 and del Carmen Nava Guerrero, 2016); however, despite the efforts made, the progress of improving access and functionality of water services and infrastructure in the last six years is low (Knipschild, 2016) and is shown in Figure 2. The progress is hindered by a considerable amount of WPs failing; this is due to the lack of funds, policy restrictions to subsidy allocations, and community involvement in operating and maintaining WPs (del Carmen Nava Guerrero, 2016).

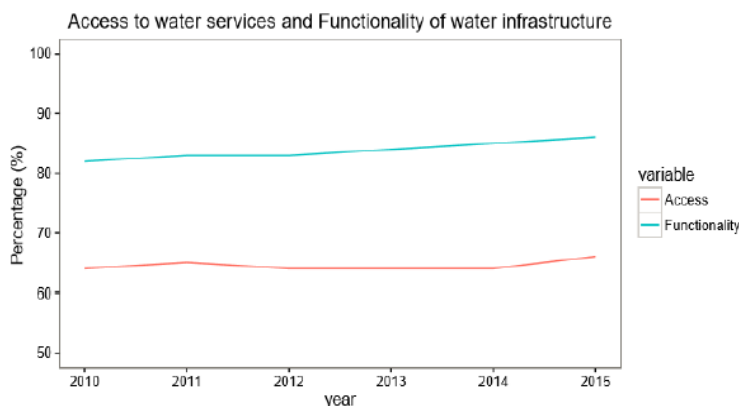


Figure 2: The development of access to safe water and functionality of water infrastructure in Rural Uganda from 2010 to 2015 (both shown in percentages). Graph made by Knipschild (2016).

A recent discussion in Uganda's water, sanitation and hygiene (WASH) sector, suggested the ability for the sector as whole to learn and adapt could influence the ability to overcome current and future challenges (Casella & da Silva Wells, 2014). Social learning (SL) is currently applied in the WASH sector to improve the functional lifetime of WPs throughout its life cycle (Knipschild 2016). Through improving the functional lifetime of WPs, the WASH sector aims to achieve a basic level of water service levels (WSL) (van Tongeren, 2014). WSL is an indicator to measure the performance of the WASH sector, and to allow actors to set goals accordingly because it also contains national standards aimed to be met. WSL is categorized in five different measurement levels and is shown in Table 1 below.

	Quantity (l/c/d)	Quality	Accessibility (mpcd)	Reliability	Status
High	>60	Good	<10	Reliable/secure	Improved
Intermediate	>40	Acceptable	30		
Basic (normative)	>20	Acceptable	30		
Sub-standard	>5	Acceptable	60		
No service	<5	Unacceptable	>60	Unreliable/insecure	Unimproved

Table 1: Acceptable definitions per characteristic, the first column from the left represents the level of WSL [Moriarty, 2010], l/c/d – litres per capita per day, mpcd – minutes spent per capita per day to gather water including the time taken to travel and crowding at source

The WSL contains following characteristics for measurements:

- 1) Access – measures the distance an individual would require to travel from their household to gather water from a safe source (WP)
- 2) Crowding – the amount of people using one particular source
- 3) Quantity – measures the amount of water an individual could gather from a safe source, in litres per capita per day (lpcd)
- 4) Quality – measures the amount of harmful chemical and biological elements in the water an individual receives
- 5) Reliability – measures the amount of time a water access point is functioning properly in relation to its expected lifetime.

Each of the above mentioned characteristics contains a definition of what is an acceptable WSL measurement. Combining the results of these characteristics yields the WSL and it could be placed on a scale to determine performance. The WSL is determined by the lowest scoring characteristic when the characteristics do not all score at the same level (van Tongeren, 2014). An acceptable level of WSL is only met when all of the characteristics meets the minimum conditions set for its own category (van Tongeren, 2014).

From Table 1, the basic WSL of which the WASH sector is currently aiming to achieve include the following characteristics: 20 litres of safe water access for domestic use per capita per day, acceptable quality, 30 minutes spent for water collecting purposes per capita per day, and WP is reliable or secure. While the quality of the water from WPs are not measured in the field currently, reliability and crowding is measured through accessibility and quantity implicitly.

The current WSLs are below the basic normative standards in those rural areas, and water services are not available for long periods of time in parts of the country; because the WASH sector is trying to achieve a basic level of WSL in the rural areas of Uganda (van Tongeren, 2014) and to provide sustainable water services (Knipschild, 2016). Improving WSL is an important matter in Uganda's WASH sector, as it could affect the health of 80% of Uganda's population (trading Economics, 2015).

1.2 Resource scarcity: groundwater

From section 1.1, the RWSD situation was introduced along with the challenges the WASH sector is facing currently. A different challenge with regards to the RWSD situation in Uganda was identified by the author under an Industrial Ecology perspective. In this section, the identified problem will be introduced and explained using tools and perspectives commonly used in the field of Industrial Ecology. This perspective is important to the thesis project, as it forms the underlying reason why this thesis research project was performed.

As mentioned in section 1.1, the WASH sector is currently implementing measures to increase WSLs in terms of water quantity made available for rural domestic use through

increasing the functionality of WPs. According to this insight, the demand for GW increases. Long term GW supply for domestic use in the rural areas is one of the goals in the WASH sector as well, and it would imply GW resources are required to be sustainable with or without resource management. In the field of Industrial Ecology, life-cycle thinking (LCT) is a common perspective used to identify problems and in design. A brief LCT analysis was conducted to assess whether the current practice of RWSD is sustainable, by examining the GW flow cycle and existing practices for GW sustainability with regards to RWSD. GW scarcity was identified by the author with regards to the RWSD situation based on the the results of the LCT analysis. The full LCT process, analysis, and insights can be found in Appendix A and the key findings from the LCT analysis is given below.

The balance between GW inflows and outflows was explored in the LCT analysis. The data examined from the Food and Agricultural Organization of the United Nations' (FAO) database AQUASTAT, suggested no GW recharge within Uganda (FAO, 2014); because 100% of the GW recharge drains into river streams and forms the base river flows in a humid and landlocked country such as Uganda (FAO, 2014). The imbalance between GW recharge and GW extraction in Uganda lead to the insight of GW storage levels dropping continuously, despite the ongoing efforts to maintain GW levels through the means of only extracting volumes less than the estimated GW recharge flows.

The imbalance between inflows and outflows of GW is expected to grow further apart due to the goals set by the WASH sector. The potential unacceptable consequences from the effects of GW depletion was explored in the LCT analysis. GW depletion could lead to water insecurity and water quality degradation, of which the effects are unfavourable for the WASH sector. It is important to note that the analysis only reflect the general situation in Uganda and the GW recharge in Uganda was assumed to equal the low flow river stream in Uganda for this study.

Through the insights gained from the LCT analysis described above and in Appendix A, the following conclusion could be drawn for the GW situation in Uganda: GW resources are under increasing depletion pressure in Uganda. By translating this conclusion in terms for RWSD in the WASH sector, it becomes the problem statement for this thesis project. The problem statement is as follows:

Due to the ongoing interventions in the WASH sector to increase WSL for RWSD, GW extraction for domestic use enhances GW depletion, leading to unsustainable effects in the environment and the service itself.

1.3 Research direction

In section 1.2, the problem of GW scarcity was discussed; and the problem statement for this thesis project was derived from the conclusion of the problem analysis explained in Appendix A and in the previous section. A direction of research was proposed to address the problem statement. In this section, the research direction will be described.

As mentioned in section 1.2, the demand for GW is expected to increase in the future as the commonization of SL is taking place in the WASH sector. However, the LCT results does not

reflect Uganda's GW resource is adequately ready for this increase of demand; because all of the annual GW recharge forms the base flows of rivers and streams in the country and lowered GW levels was observed in the recent years. GW management is therefore needed to ensure water security in Uganda; aside from controlling extraction through issuing and revoking permits.

The proposed direction to study as a potential solution direction to the problem was to explore social learning (SL) for GW management in Uganda's rural water supply. SL was recommended because it is a commonized method in Uganda's WASH sector for tackling current and future challenges (improving WSL in this case) and SL has been researched for water resource management. However, the application of SL in the WASH sector should not be applied solely towards water resource management. Instead, the application of SL should be concurrently applied for both improving WSL and water resource management (maintaining GW levels (GWL)). This is because GW resources and base safe water access are both important issues which are interconnected and need to be addressed at the same time. The concurrent application of SL was suggested because of the interconnection between the two issues. Applying SL only for WSL would be unsustainable for the service and the environment overtime, and applying SL only for resource management would hinder the progress of improving WSL for the people living in rural areas of Uganda.

Due to the reasons mentioned above, the research direction of applying SL was chosen to be explored upon. Research questions were derived and the scope of the research was set based on this research direction. Section 1.3.1 contains the description of the scope of research and research questions set out to answer for this thesis research project.

1.3.1 Research questions and scope

In section 1.3, the idea of applying SL concurrently for WSL improvement and GW resource management was proposed. From this idea, the ideal research question would be: What effect does SL have on GWL when SL is applied concurrently for WSL and GWL management? However, due to time constraint and lack of expertise, the scope of the study was limited to only explore the effect SL has on GWL when SL is applied to GW resource management. The scope was further reduced to a specific GW resource management strategy because there are a range of different management strategies, namely rationing, community based management, water trading, retention, reuse and recharge. The chosen strategy for this study was rationing, as it is a common response to GW decline and other reasons explained in chapter 4 of this report. Since real life study is not possible for this study, simulation is needed. Agent based modelling (ABM) was chosen as the simulation method for this study because of its advantages as well as synchronizing this study with the work done by Knipschild in 2016 previously on social learning in Uganda's RWSD. A full explanation on why ABM was chosen with regards to other simulation tools is included in chapter 5. A main research question for this study could be formed based on the reasons stated above, and it is as follows:

RQ: How can social learning be conceptualized and modelled for GW rationing in Uganda's rural domestic water service delivery?

The research question sets the direction and main focus of the research. It is used to guide the types of activities needed to answer at the end of the research process. In order to answer the main research question, sub-questions were generated. Attaining answers to the following sub-questions contributes to answering for the main research question.

SRQ1: How to model and conceptualize social learning

SRQ2: How should rationing for GW resource management be performed in the model for Uganda's RWSD?

SRQ3: What is the landscape of which social learning and GW interacts in Uganda?

The first sub-question was designed to answer the first part of the main research question on social learning. The second sub-question was designed to answer the middle part of the main research question on GW rationing; and the third sub-question was designed to answer the last part of the main research question about the WASH sector in the rural areas of Uganda.

By answering the main research question and sub research questions, insights could be gained for the ideal research direction mentioned in the beginning of this section. As a result, the product of this thesis is a contribution to the research community as a case study, where GW resources are studied in the perspective of SL; as well as raising sustainability awareness in the WASH sector. The product of this thesis contributes to the research community because previous research on SL were aimed at improving WSLs only for Uganda (Knipschild, 2016), and how SL could be applied for water resource management in sustainability (Pahl-Wostl, 2008). The case studies by Pahl-Wostl (2008) were not Uganda and GWL specific and GWL interactions were not included in Knipschild's study; therefore the effect SL has on GWL is unknown for Uganda's WASH sector regardless of whether it is applied concurrently or for GW management only. This exploratory study addresses the knowledge gap, by presenting insights which fill the knowledge gap about the effect SL has on GWL when it is applied for GW management only. In the next section the structure of which this report will present the study of these insights is explained.

1.4 Thesis report structure and research approach

The research approach for this study is divided into four parts: (I) Defining research area, (II) Learning, (III) Design and model building and (IV) Applying and reflecting. Background information regarding the area of the study are presented in Part I. In the current chapter, the research purpose, problem, direction, scope, and questions were explored and contextualized. In Part II, the sub-questions are addressed through learning from literature research and reporting. First, in Chapter 2, how social learning could be translated into a simulation is presented. Then, in Chapter 3, the landscape of which SL and GW rationing will be applied in the simulation study is presented. In Chapter 4, key conceptualizations and decisions towards how rationing for GW resource management for RWSD in Uganda for this study is presented. In Part III, the insights and answers gained in Part II are combined and applied into model design and model construction. In Chapter 5, the design decisions on how social learning, rationing, and the landscape is incorporated in the model is conceptualized and discussed. At the end of Chapter 5, the main research question along with all the sub-questions are answered. In Part IV, the model is applied to an experiment to generate insights towards the ideal research direction. In Chapter 6, the details of the experiment, expected

results, and the questions this experiment is aimed at to answer in order to gain insights to the research direction is described. In Chapter 7, the results of the experiment is documented. In Chapter 8, the analysis of the results and the insights gained from the experiment is presented. At the end of Chapter 8, the questions presented in Chapter 6 is answered. Lastly, in Chapter 9 and 10 , the conclusions of this study and recommendations for future research are presented respectively.

2. Social learning

In chapter 1, social learning (SL) was proposed to be applied in Uganda for GW management and rural water service delivery improvement. SL was proposed because it is a commonized method in the WASH sector for tackling current and future challenges and SL has been researched for water resource management. Although the focus of this study was set on only exploring the effects SL has on GWL when it is applied for GW management, functional processes of learning and learning effects from SL are similar to when SL is applied to both issues concurrently or when it is applied separately.

The necessary background information about SL for this study can be found in Appendix B. The explanations in Appendix B contain literature reviews to the following topics: who learns, what is social learning, how SL takes place, how is SL applied in sustainability sciences, the influence of SL in sustainability and what could be learned. The purpose of this chapter is to explain the theory behind how SL was conceptualized in the model design.

According to Knipschild (2016), modelling learning can be done by using the theory of memetics and evolution as it enables a modeller to encode learning into a computer model. When comparing Knipschild's (2016) model of learning with the SL literature in Appendix B.4, parts of the SL process are omitted in Knipschild's (2016) model, such as: relational activities and the formation of the problem, trust between actors, and the raise of the network itself. Due to time constraint of the project, an assumption was made where Knipschild's (2016) way of modelling learning is sufficient for this study. In the next section, an explanation is given on how memetics can be used to conceptualize SL.

2.1 Relation between memetics and SL

The theory of memetics could help in providing an understanding of why certain outcomes surfaced from the SL process, by conceptualizing how to trace and measure what one has learned from SL. In this section, the theory of memetics and how memetics theory contributes to the understanding of SL processes is explained and discussed.

In memetics, the focus is placed on how do humans learn from the transfer of different pieces of information; rather than focusing on how do humans learn from performing different activities explained in Appendix B.2 to B.4. The general learning process of memetics is as follows: the piece of information is first encountered by a human, he or she could decide to add, subtract, change, or do nothing with the piece of information they have encountered, and finally the carrier of this piece of information could decide whether or not to pass on this piece of information to another human (Knipschild, 2016). The piece of information evolves over the number of transfers and stops evolving when one decides not to pass on or make changes to the piece of information (Knipschild, 2016).

Humans encounter at least two types of information: genes and memes, of which both are influencing human conditions (Knipschild, 2016). A gene represent a unit of biological information, whereas a meme represents a unit of cultural information (Knipschild, 2016). Due to the evolving nature of genes and memes, the necessary conditions for evolution applies

(Knipschild, 2016). The necessary conditions are replication, variation and selection, and they are present in both types of information (Knipschild, 2016). A human gene is normally replicated through giving birth, varied through mating or other forms of variation, and selected by potential mating partners and the surrounding environment to survive onward or not (Knipschild, 2016).

A meme can be understood as an information pattern stored in a person's memory and could be replicated by copying it into another person's memory (Knipschild, 2016). A meme is varied through the carrier if one wishes to do so by adjusting the meme before letting another person copy it, and selected through the social environment one is placed in (Knipschild, 2016). In the context of social learning, the concept of a meme is appealing because the process is similar and could be used to further explain the concept of social learning. At the individual level of social learning, memes could be transferred through observation, copied by how well one remembers the meme (retention), reproduced by one's ability to reproduce the meme from memory (reproduction), and selected by one's motivation and attention. Memes could also be transferred between individuals and groups through SL activities. For example, one of the important elements within a SL process in resource management is the construction of a frame; memes are transferred, copied and learned when actors are voicing their memes, interpretation and negotiations are SL activities of which actors could adjust and select memes. A new meme is constructed when a frame is reached from the SL process, and the actors involved are the carriers of this new meme. Therefore, a meme contains the content one has learned through these processes. The activities executed in SL processes enable learning by shaping, coping, and transferring memes between people.

From this chapter, the use of memetics to conceptualize SL for computer modelling was explained and discussed. The insights from this chapter was used in the model design and the analysis for this study, which are documented in chapters 5 and 7 respectively in this report. Thus, a part of the first research sub-question was answered in this chapter. SL was conceptualized using memetics, processes and activities; and how to model SL will be explained in chapter 5. Landscape of the rural water service delivery Uganda will be discussed in the next chapter. In other words, where SL is applied in the context of this research will be explained.

3. Landscape of the rural water service delivery

From chapter 1 and Appendix A, the RWSD and GW situation was explored and the related concerns of GW levels were explained. SL was proposed to be explored and studied upon in this research to address the identified problem. In chapter 2 and Appendix B, an overall description of SL was given to define how SL should be perceived in this study and what are the SL processes and activities in the domain of sustainability. In this chapter, the landscape of which SL was proposed to be applied into for this research to address the problem of GW sustainability for RWSD will be discussed. The aim of this chapter is to provide an understanding of how the WASH sector is functioning to provide water services to the rural areas of Uganda and how to conceptualize the WASH sector for this study. The conceptualization of the RWSD landscape will serve as a reference point to understand how SL is affecting WSLs and applied in Uganda's WASH sector, who is involved in the SL network currently, and where are the boundaries of the proposed area of research.

According to Knipschild (2016), the structure of the WASH sector landscape can be defined using MLG; and the author's full interpretation as to why Uganda's RWSD structure can be conceptualized using MLG is explained in Appendix C. Apart from the reasons discussed in Appendix C, Knipschild's (2016) way of conceptualizing the WASH sector using MLG was chosen and assumed to be sufficient for this study due to the time constraint of the research as well. In section 3.1, the relevant actors within the WASH sector is described; followed by an explanation on how Knipschild (2016) conceptualized Uganda's WASH sector under MLG in section 3.2. Since the landscape of RWSD also include technology and the environment besides humans; therefore in section 3.3, the landscape which contains all three elements is conceptualized and explained using the systems perspective.

3.1 Actors within the WASH sector

There are different actors within the WASH sector to ensure sustainable water services in Uganda, and could be categorized in five different domains: service authority, service provider, users, civil societies and international development organizations (Casella, van Tongeren & Nikolic, 2015). The service authority is legally responsible for service delivery planning, coordination, regulation, monitoring and sanctioning water service providers (Casella, van Tongeren & Nikolic, 2015). Providing technical assistance to water providers is also part of the service authority's responsibility (Casella, van Tongeren & Nikolic, 2015). The service provider(s) are responsible for daily water services, and these services include: operation, maintenance and administration of the water supply infrastructure (Casella, van Tongeren & Nikolic, 2015). Users in the context of this study are households located in the rural areas of Uganda and utilize the rural water supply infrastructure to gather water for domestic uses. Civil societies are responsible for conveying the needs and wishes of the users, and some societies are service providers as well (Casella, van Tongeren & Nikolic, 2015). Functions of international development organizations varies among different organizations, and could be see as an entity which aids the other categories as an organization sees fit. Formal and informal arrangements between actors from the above mentioned categories are required to ensure sustainable water services (Casella, van Tongeren & Nikolic, 2015). Casella, van Tongeren & Nikolic (2015) described these

arrangements as: “ policy-and decision-making processes about responsibilities and actor relationships through which the power, responsibilities, norms, values and formal agreements embedded in laws and policies are negotiated among and implemented by the array of stakeholders, whose roles and responsibilities may overlap. ” These arrangements create an interdependent network consist of multiple actors or agents across different administrative levels (Casella, van Tongeren & Nikolic, 2015), and represents the WASH sector's structure under governance.

3.2 Conceptualizing the WASH sector under multi-level governance (MLG)

There are different administrative levels of which the above mentioned actors in section 3.1 functions within Uganda's WASH sector. The combination of governance at each level forms the governance structure of the WASH sector, and therefore the structure should be observed at multiple institutional level using a multi-level governance (MLG) approach (Knipschild, 2016). Five different institutional and administrative levels across the WASH sector's governance structure were identified by Knipschild (2016), and these levels include: national, regional, district, (sub-)county, and village. There are multiple regions in Uganda and each region is composed of multiple districts (Knipschild, 2016). There are 111 districts in Uganda, and each district is composed of counties (Knipschild, 2016). The counties are further divided into sub-counties and each sub-counties consist of villages, parishes and communities (Knipschild, 2016).

At the national level is where the Ministry of Water and Environment (MWE) and Ministry of Finance (MoF) governs the WASH sector. The MWE is responsible for rational and sustainable utilization, development and management of water resources, setting national policies and standards, regulating water resources, and determining priorities for water resource management (Knipschild, 2016). There are three directorates within the MWE, of which the Directorate of Water development (DWD) is in charge of the delivery of domestic rural water services (del Carmen Nava Guerrero, 2016); “ the Directorate of Water Resources Management (DWRM) is responsible for developing and maintaining national water laws, policies and regulations; managing, monitoring and regulation of water resources through issuing water use, abstraction and wastewater discharge permits” (MWE, 2017a); and the Wetlands Management Department (WMD) which is responsible for managing “wetland resources and to sustain the biophysical and socio-economic values of wetlands in Uganda for present and future generations” (MWE, 2017a). DWRM issue permits for GW extraction and drilling to registered companies for RWSD, and these companies are obliged to submit hydro-geographical data every 3 months for review (MetaMeta, 2010). There are parastatal institutions within the MWE as well, one of which is the National Environmental management authority (NEMA), and it is responsible for enforcing existing regulations on environmental management in Uganda and monitor relevant activities performed by actors at the national and local government level (MWE, 2017b). However, the dynamics of how GW is managed is currently unclear at this level, and it is to be researched during the study. Lastly, the Ministry of Finance (MoF) also operates at the national level because the MoF provides financial support for the MWE (Knipschild, 2016).

At the regional level, there are WASH alliances and technical support units (TSUs) (Knipschild, 2016). TSUs provide technical support, technical advice and technical training for

districts, monitor progress in the sector, identify best practices, report to the MWE, and to ensure districts are adhering to national policies (Knipschild, 2016). There are 8 TSUs in total, each covering between 8 to 20 districts (Knipschild, 2016). District representatives come together and share experiences with one another at WASH alliances (Knipschild, 2016). Although these alliances are self organized either together with international organization or local organizations, these alliances are allowed to operate and external control is not required as long as the operation stays within the limits and goals set by the external agent.

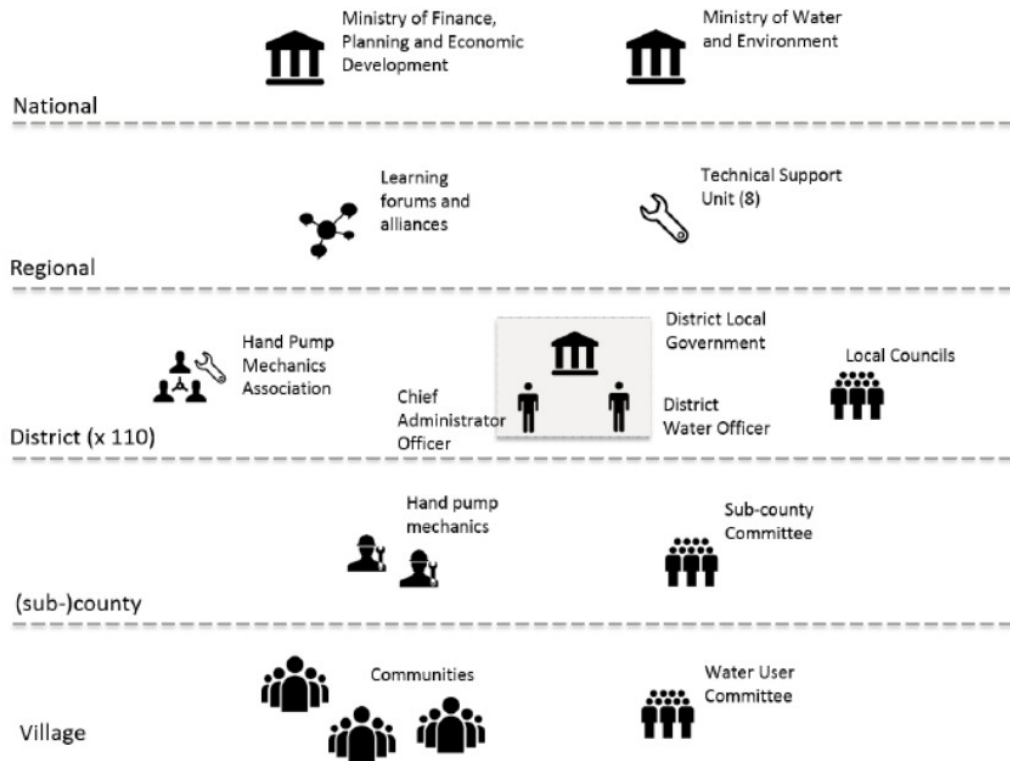


Figure 3: An overview illustration of the multi-level governance structure of the WASH sector (Knipschild, 2016)

At the district level, there are district local governments (DLGs), hand-pump mechanics association (HPMA), and local councils (LCs) at each of the 111 districts (Knipschild, 2016). Within DLGs, district water offices (DWOs) are present and are representatives from the MWE (del Carmen Nava Guerrero, 2016). DLG and DWOs are responsible for implementing rural water activities in their respective districts (Knipschild, 2016). These activities include assessing, planning and implementing management activities of wetland resources, and “planning, monitoring, installing, and conducting major repairs on WPs” (del Carmen Nava Guerrero, 2016). DLG also works with NEMA at the national level, as DLGs are performing and relaying monitoring and assessments of environmental reports (NEMA, 2017). LCs are elected governments that operate at each district and there are no representatives from the national level present. There are multiple levels of hierarchy within LCs, ranging from LC1 – at the village level - to LC5 – at the district level (Knipschild, 2016). LCs are responsible for operations and minor maintenance support activities at WPs (Knipschild, 2016). As LCs and

DLGs are separate forms of government, LCs cannot convey messages directly to the national level on paper and must do so via DLGs (Knipschild, 2016). DLGs operate under governance, as these institutions were given orders and specific goals from a top-down approach; LCs are self governing entities from a bottom-up approach (self organization) of which operates within governance with external control. HPMA is where experiences and knowledge is spread between mechanics and where mechanics could purchase cheaper parts for their repair services (Knipschild, 2016).

At the sub-county level, there are committees and hand pump mechanics (HPMs) (Knipschild, 2016). HPMs provide services to both DWOs and LCs to conduct maintenance that excess local capabilities and their capacities are supported by the TSUs (Knipschild, 2016). The committees monitors and coordinates water activities, and these activities ranges between district and village level (Knipschild, 2016). Water service committees (WSCs) are responsible for day-to-day operations of the water infrastructure at the village level (Knipschild, 2016). Representatives from the community forms WSCs and are in charged with money collection, small maintenance (i.e. keeping the WP area clean) and administration (Knipschild, 2016). Water users are at the village level as well, and are governed by the above mentioned multiple interlinked levels of governance (Knipschild, 2016). Developing organizations operate at all levels to improve WSLs through direct support, facilitating, training and advocacy (Knipschild, 2016). Therefore, the WASH sector in Uganda operates under governance in a multi-level, multi-actors and multi-organizational (self organization, self governance and governance) structure, to achieve the public goal of providing rural water services within set conditions. An overview illustration of the multi-level governance structure of the WASH sector is shown in Figure 3.

3.3 Systems perspective

In the previous section, the WASH sector was described using MLG. Besides the WASH sector, RWSD requires a set of other elements in order for the service to be operational. Resources and technologies are the other elements which are constantly interacting with each other for RWSD. While resources belong in the environmental dimension and technologies belong in the technical dimension, the use of MLG is insufficient to describe the landscape of interest because it is only describing the social dimension. The social dimension consists of different current actors, policies and (SL) activities aimed at improving WSL and maintaining GWLs. The technical dimension contains different water supplying and recharging technologies; and only hand pumps at shallow wells were considered in this study to stay consistent with the previous work done by Knipschild (2016) in the same domain. Lastly, the natural environment of which the RWSD is interacting with belongs in the environmental dimension, such as gases exchange to the atmosphere, materials needed for the technologies, and natural resources affected by the activities in RWSD. GW is the only element considered in this study due to the scope of the project. A new perspective is needed to integrate the social, technical and environmental dimension to describe the landscape.

By framing RWSD as a system that is open to feedback from its environment, the landscape can be conceptualized and investigated. Through treating the three above mentioned dimensions as sub-systems under a unified system, the dynamics between each dimension can be studied under the systems perspective. In order to understand the systems

perspective, the definition of a system is needed.

“A system is defined as a collection of elements that continually interact over time to form a unified whole.” (Sweetser, 1999). According to this definition, RWSD in Uganda could be seen as an unified whole: a water service delivery system in the rural areas of Uganda, and of which some of elements in this system include: end users, MWE, WPs, WSLs and GWs. The RWSD system in Uganda is considered a complex adaptive system (CAS), because the elements and actors in the system are constantly acting and reacting to each other in parallel (Casella, van Tongeren & Nikolic, 2015). The RWSD system is complex, because unlike linear systems, the results from an intervention in such a system is non-linear cannot be easily predicted (Knipschild, 2016). Some of the other properties of complex systems include: diversity, path-dependency, observer-dependency, emergence, nestedness and evolution. Competition, cooperation and decision making from agents are required if there is any coherent behaviour in CAS (Casella, van Tongeren & Nikolic, 2015).

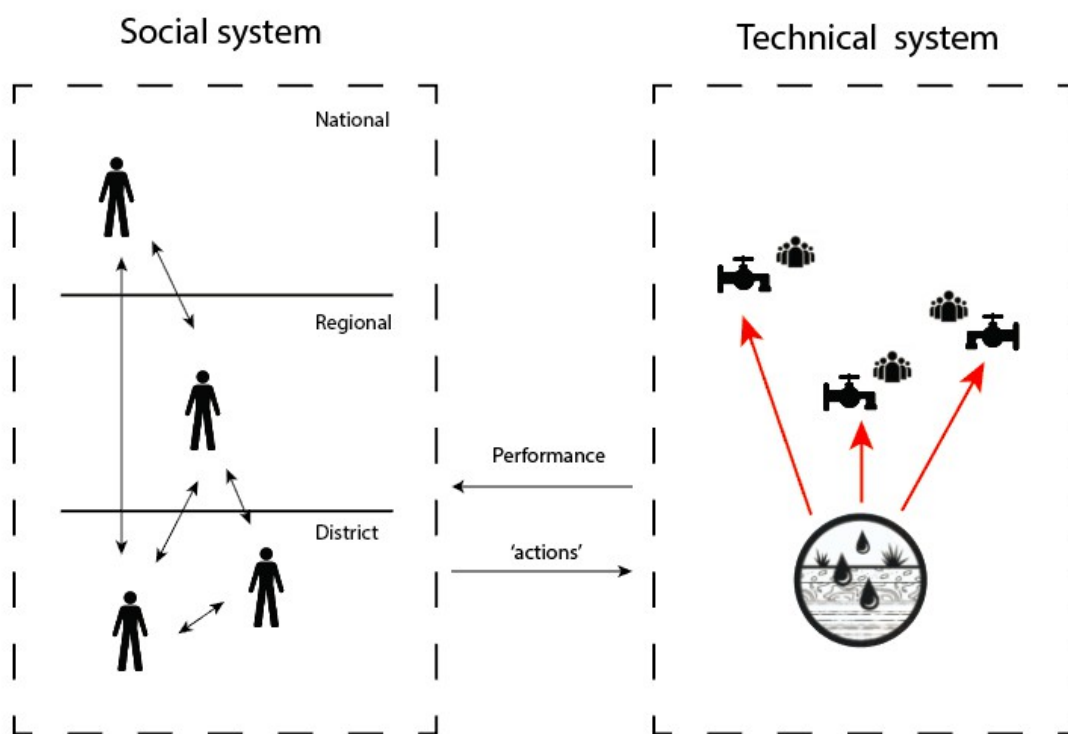


Figure 4: Abstract illustration of the STS considered for this study in the context of Uganda's rural water supply system adapted from Knipschild (2016). The black arrows represent interactions, red arrows represent limitation, multi-level governance is represented by the division of the social system, and water users, water points and GW in located in the technical system.

Socio-technical systems (STS) is a type of CAS which is useful for conceptualizing the rural water sector into a CAS and STS was also used in Knipschild's (2016) conceptualization of RWSD system in Uganda. “Socio-technical systems are comprised of ‘two deeply interconnected subsystems: a social network of actors and a physical network of technical artifacts’. These systems consist of ‘heterogeneous decision making entities and technological artifacts’ and ‘are governed by public policy in a multi-scale institutional context’ ” (Casella, van Tongeren & Nikolic, 2015). In Uganda's WASH sector, the hand pumps located

at WPs are the technical artifacts for RWSD, embedded in a multi-level governance social network. However, the environmental dimension is not included in STS in general and in Knipschild's (2016) version of the STS. Social-ecological systems (SES) is another type of CAS of which all the above mentioned dimensions are included. Due to the lack of insight on the environmental system (GW hydro-geology), the STS was adjusted to include a simplified version of the environmental dimension inspired by the format of SES. This was done by treating GW as a limit in the technical dimension. A brief description is given in Appendix D on how to conceptualize Uganda's RWSD as an SES.

In Figure 4, the considered RWSD landscape for this study is shown. Actors under MLG are located in the social dimension, which in turn has an influence in the technical system. The technical system contains the hand pumps of which are required for RWSD to be functional. All artifacts in the technical dimension are connected to an overall limit which represents GW in the environmental dimension, and the limit is influenced by the performance of each artifact. All artifacts will cease to work if the limit is reached. The technical dimension will also influence the social dimension based on the performance of the artifacts and the limit.

Thus far in this chapter, the choice of using MLG and STS for this study was mainly justified using previous research work done by Knipschild (2016) and from a MLG or systems perspective. However, the author also made an attempt to defend the choice of using MLG and STS for this study from a SL perspective; in order to verify theoretically whether SL as a concept is applicable under the defined and proposed perspectives of MLG and STS. For more information on the role of social learning in the proposed landscape, such as: why is SL applicable in the context of MLG and the influence of SL under MLG and CAS can be found in Appendix E.

From this section, the RWSD landscape in Uganda was described using MLG and under the perspective of STS with a limitation in the technical dimension to address GW resources for the purposes of this study. Thus, the third research sub-question was answered in this chapter. The landscape of which social learning and GW interacts in Uganda was conceptualized using MLG and STS. The proposed strategy of using SL to address GW depletion was suggested to be applicable in the proposed landscape of consideration in this chapter, through the insights gained from literature reviews. In the next chapter, the discussion continues on how GW resource management was conceptualized for this study, in order to answer the second research sub-question: how should rationing for GW resource management be performed in the model for Uganda's RWSD? In other words, an explanation will be given on the dynamics between the social and technical dimension for RWSD in the context of this study.

4. Rationing for GW resource management

From the previous chapter, the RWSD landscape was described using MLG and STS. This chapter will focus on the dynamics between the social and technical dimension for RWSD in the context of this study. Before discussing the mentioned dynamics, a brief explanation will be given on why rationing was chosen as a GW resource management strategy for this study in section 4.1. In section 4.2, the mentioned dynamics will be explained in terms of how GW rationing was conceptualized to function in the proposed STS with SL.

4.1 GW rationing as a resource management strategy

In this section, a brief explanation will be given on why rationing was chosen for this study. In chapter 3, RWSD was described as a MLG integrated STS, and the concept of control was discussed. Under the theory of governance, there is a certain level of control within the system from the actor(s) involved from a bottom up or top down approach within the social dimension. Therefore, the assumption of one or more actors in the described system containing the power and the means to restrict GW extraction at WPs can be made.

While the methods of exercising power to restrict GW extraction is outside of the scope of this study, examples of such methods include imposing fines and shutting down WPs. This assumption was made with the support of a past example of drought management in California, USA; where pumping of GW was regulated to address GW depletion (Nijhuis, 2014). Another source of inspiration and confirmation for this approach was found in Chevalking, Knoop & van Steenbergen's report in 2008; where restriction of GW use was one of the ideas for GW resource management, as it was implemented in Saudi Arabia, India, Pakistan and Italy (Chevalking, Knoop & van Steenbergen, 2008). Hence, the choice of selecting GW restriction was justified.

Due to time constraint, a brainstorm to the author's knowledge based on the above mentioned arguments for how GW resource rationing can be carried out under regulation was conducted, instead of interviews with experts. The considered options were as follows:

- 1) Limits functional time of WP (Time of day / pump)
- 2) Limit total amount of water pumped at each WP
- 3) Limit amount of water pumped at each WP per agent
- 4) Force agents to walk further for water
- 5) Limit amount of functional WPs in a district

Since water collection behaviour data was unavailable to the author at the time of the brainstorm, the first option was neglected. The fourth option is implicit in the second and third option, therefore it was eliminated as well. The last option was also eliminated because it is conflicting with the current financial grant conditions in the WASH sector, as more than 50% of the conditional grant must be used to expand the amount of WPs (Knipschild, 2016). The second option was selected to study upon, because opportunities for water users (WUs) to meet the national target of 20 L/p/d at the nearest WP are present under rationing; whereas the third option requires WUs to travel to multiple nearby WPs to meet the national target,

because the ration method under the third option would mean WUs could only collect less than the national target at all times. An assumption was made where the WASH sector would prefer the second option over the third option because of the possibility to allow WUs to collect 20 L/p/d from one single WP while rationing. Based the above assumptions, limiting the total amount of water pumped at each WP was selected to be rationing method for this study. Apart from the above assumptions, GW rationing was also argued by the author to be able to bring change in the proposed STS and under SL within the context of this study. Further explanations on how GW rationing could bring change in the context of the proposed STS and SL for this study could be found in Appendix F.

From this chapter, the selection of GW rationing as chosen the resource management strategy for this study was defended by its relation to the other theories used in this study and a series of assumptions made about the preference for the selected GW management strategy. The insights described in chapters 2 through 4 were integrated and translated into a model simulation in ABM in the next chapter, in order to work towards the answer for the main research question and the second sub-question of this study.

5. Model design

From chapter 1, the main research question for this study was set out to find the answer to how to conceptualize and model social learning for GW rationing in rural areas of Uganda for domestic use. Since real life study is not possible for this study as mentioned also in chapter 1, simulation is needed to answer the main research question and ABM was chosen as the simulation method for this study. Besides synchronizing the product of this study with the work done by Knipschild (2016), ABM contains other functional advantages over other simulation techniques. In Appendix G, an explanation is given on why ABM was chosen as a suitable method for this study when compared to other simulation techniques for CAS.

In chapters 2 to 4, key insights about SL, GW rationing and Uganda's RWSD landscape were described; and in this chapter, an explanation will be given on how the above mentioned insights from the previous chapters were translated into a model design concept. In order to understand how the model was designed and integrated the insights described in the previous chapters, an introduction will be given on the core concepts and practice guidelines of ABM in section 5.1. In section 5.2, translated model conceptualizations of SL, rationing and landscape will be explained. The concepts were further translated into ABM modelling environment and its design details are described in section 5.3. The constructed ABM model is shown in section 5.4; and finally, designed tests and results to prove the constructed ABM was indeed functioning correctly is shown in section 5.5.

5.1 What is ABM and practice guidelines

Advantages of using ABM for this study was described in Appendix G; however, the question of how to practice ABM in general remains. In this section, the design methodology used to practice ABM will be included along with an introduction to the core concepts of ABM. The core concepts will be used in the other remaining sections of this chapter to explain the design details of the model.

There are 10 steps to practice ABM (Dam, Nikolic & Lukszo, 2013), and these steps were followed for the execution of the model in this research. The list below contains the steps to systematically practice as suggested by Dam, Nikolic & Lukszo (2013):

- Step 1: Problem formulation and actor identification
- Step 2: System identification and decomposition
- Step 3: Concept formalization
- Step 4: Model formalization
- Step 5: Software implementation
- Step 6: Model verification
- Step 7: Experimentation
- Step 8: Data analysis
- Step 9: Model validation
- Step 10: Model use

The first step was done through the described insights from chapters 1 to 4 of this report. The results of step 2 to 6 will be explained through the model design details later in this chapter; and the results from remaining steps is included in the other remaining chapters of this report. The ABM design details will be explained in section 5.4 and 5.5 using the core concepts of ABM; therefore, a brief introduction to the key components of ABM is given below.

“An ABM is a computational model for simulating actions and interactions between autonomous agents.” (Knipschild, 2016). There are three core concepts in ABM, namely agents, environment and time (Knipschild, 2016), and they are required to be designed and included in an ABM. An agent is the smallest element in an ABM and it is an autonomous entity (Knipschild, 2016). Agents perform actions based on a set of designed states and rules, which could in turn influence themselves, other agents or the environment in the simulation (Knipschild, 2016). Agents interact and react to each other in ABM; therefore, agents could also perform actions as a reaction to the received inputs from the environment, as well as the actions and states of other agents (Knipschild, 2016). Different types of agents can exist within a model, and agents with different characteristics, states and rules of the same agent type could also exist in the same model.

The environment is the space of which agents exist, act and interact with each other in an ABM (Knipschild, 2016). It contains everything that affects agents, except the particular agent itself (Dam, Nikolic & Lukszo, 2013). In other words, the environment provides a structure or space for the agents to interact in and all the information of which agents can use for their decision making processes besides the information of the particular agent itself (Dam, Nikolic & Lukszo, 2013). The environment can be static or dynamic and change over time; designers can design the environment in a certain way for agents to interact or the environment could be change through agent-environment interactions (Knipschild, 2016).

Time is the third component in the anatomy of an ABM (Knipschild, 2016). Discrete time is used in ABM and the smallest unit of time is represented by a tick (Dam, Nikolic & Lukszo, 2013). A tick can be redefined by the designer to represent different length of time (Dam, Nikolic & Lukszo, 2013). Time is an important element in ABM, because an ABM simulation is not very useful when a single simulation tick takes longer than the amount of real time it was designed to represent (Dam, Nikolic & Lukszo, 2013) or the time frame of interest (Knipschild, 2016). Lastly, parallelism is assumed to occur in an ABM; which means simultaneous actions are assumed to be performed in parallel at the same time (Knipschild, 2016).

In reality, actions within CAS takes place in a parallel manner (Dam, Nikolic & Lukszo, 2013). In ABM, actions are performed one after the other; therefore, simultaneous actions are scheduled to perform in a random manner by the software (Knipschild, 2016). The assumption of parallelism matters because different outcomes can emerge based on the order these actions are scheduled to perform in.

From this section, the core components and the design methodology was described; and as mentioned in this section, an assumption was made for all ABM in general in order for the simulation tool to be valid. Due to the time constraint, a simplified version of described STS from chapter 3 was modelled to gather insights for the study; and therefore other assumptions were made in order for the insights to be valid. The main assumptions are described and

explained in the next section prior to the the explanation of the designed model; in order to understand why the model was designed to operate in the manner it was made.

5.2 Model assumptions:

A model is two steps away from reality because a model is made from the understanding of the modeller on (a part of) reality (Nikolic & Davis, 2014). In order for the designed model and the results it generates to be valid, a set of assumptions were taken. All of the assumptions taken for this study and the designed model is listed in Appendix H along with a short explanation on why the assumption was taken. The main assumptions were:

- GW recharge in Uganda was assumed to equal the low flow river stream in Uganda and therefore excluded in this study and model. This assumption was made in correspondence to the explanations in chapter 1. GW resources were assumed to be disconnected per district in Uganda and treated as separate water tanks in the model. Furthermore, GW resources in Uganda were assumed to be completely depleted in twenty years and the starting amount of GW in each district is calculated by multiplying the basic amount of WSL (20 Litres) with the maximum amount of WUs allowed in each district (110 WUs) over 20 years.
- Exact population, district area, number of WPs and location of WPs in Uganda were excluded in the model due to time constraint of the study and the information available to the author.
- The modelled system assumed twelve districts in the system. Each district was assumed to begin every simulation with ten WUs and five WPs, of which two of the WPs are unsafe type WPs. Districts were assumed to have the same surface area in the model. Geographical characteristics were excluded due to the lack of expertise and knowledge on the hydro-geology of Uganda. The maximum WU in a district was assumed to be one hundred and ten. This assumption was made because a negative value in GW levels would indicate WUs are withdrawing more than the storage which does not happen in reality.
- WUs were assumed to be able to travel freely in the district without any geographical or other constraints. WUs were also assumed to be able to know all of the locations and types of the WPs in their district. WUs will always visit the next closest source to finish their task of water collection. However, WUs will always visit the closest safe type WP first at the beginning of their water collection sequence. The population of WUs in the rural areas of Uganda was assumed to be increasing in the next twenty years due to unpredictable population patterns in the rural areas of Uganda.
- A random percentage of the water collected from the unsafe sources will be contributed to the total amount of GW in each district to represent unsafe sources which are GW based due to the insufficient information sources on unsafe water sources and the hydro-geology in Uganda at the time of this study. This assumption was made after consulting the third supervisor of this study for confirmation.
- All of the WPs in the model were assumed to be functioning all the time. The model was designed to increase only improved source type WP if a WP increase does

- occur in a district and placed randomly within each district.
- GW rationing at WP was assumed to occur as follows in the model. Each DLA will apply their ration ratio based on the expected amount of GW extraction from WUs living within a return distance of 1.5km between its starting point and the safe type WP. Each WU living within a return distance of 1.5km will increase the expected amount by 20 Litres per day and the ration ratio is a percentage of the expected amount. If no WU is expected to visit the particular WP, the expected amount was assumed to be set at one WU's worth of water. This assumption was made because rationing as a GW resource management strategy was not applied in Uganda's RWSD system at the time of the study in reality.
 - Technical limit of a WP was assumed to be 10 Litres by 60 minutes by 8 hours by 365 days (Whitehead, 2001), and only hand-pumps at shallow wells were considered in this study. This assumption was made because this project is based on the previous work done by Knipschild (2016) and the same assumption was made.
 - DLAs have full information about their own WPs, WUs, GWLs and ration ratios at all times. DLAs were also assumed to have the power to control WPs in the model. DLA will always apply what they've learned (ration ratio from the best performing district in their learning network) if they are in the bottom half of the ranking list. In other words, DLAs were assumed to only make decisions based on GWL performance. Districts belonging in the bottom half of the learning list but containing the same GW levels will never apply and learn ration ratios from the best ranking district. The learning network and frame were assumed and given to each district does not change over time in the model.
 - A tick in the designed ABM represents a year in real time and the maximum model duration was set to twenty ticks. This assumption was made because ABM operates in discrete time as explained in the previous section and the model duration was set based on Knipschild's (2016) model.

From this section, the assumptions taken into account for the model design was described and an explanation was given on why these assumptions were made. In the next section, the conceptualizations made prior to implementing the ABM for this study is documented; in order words, the results from the second and third step of the practice guideline.

5.3 ABM conceptualization

According to the practice guidelines introduced in section 5.1, the system must be identified and conceptualized prior to designing the functioning details of the model and model implementation. In this section, the insights from chapters 2 to 4 are translated into conceptualizations for the ABM. In section 5.3.1, conceptualizations of the RWSD STS will be given, following by an explanation on how SL was conceptualized in section 5.3.2 for this research study.

5.3.1 Conceptualizing Uganda's RWSD STS for the model

From chapter 3, RWSD and GWL in Uganda was conceptualized and explained using STS.

Due to time constraint, only parts of the landscape were modelled to simulate the behaviour of the STS; therefore, the focus of this section is about explaining what and who is included in the model. Figure 5 is an entity relation diagram made to illustrate the entities included in the model, what elements do each entity have and how each entity relate to each other in the system.

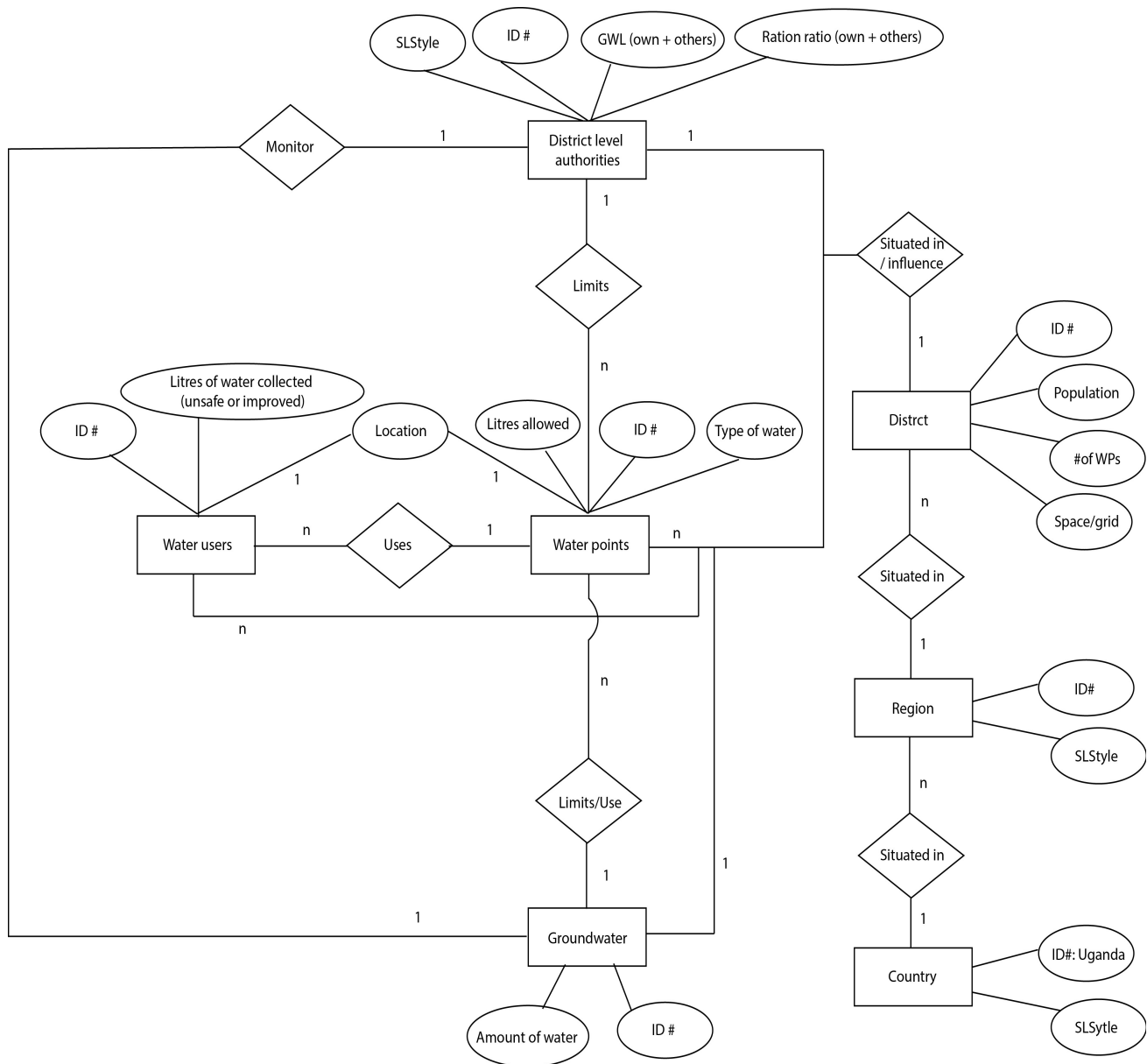


Figure 5: Entity relation diagram -where entities are in rectangles, elements are in ovals and relations are in diamond, 1 represents a relation and n represents multiple relations.

WUs, WPs, GW, district level authorities (DLAs), districts, regions and country are the seven entities included in the model. WUs, WPs and GW interact to generate performance results; districts, regions and country are where WUs, WPs and GW operate in. DLAs are included because the social dimension of the system was described using MLG, and the act of

controlling WPs could be coming from a top down or bottom up. Therefore, DLAs were chosen to be required in the model, as actors at this level could be influenced by the national level decisions and decisions made from sub-county and village level.

The entities are related directly or indirectly in the designed model. WUs uses WPs to collect water and WPs are limited by GW and DLAs. WUs, DLAs and WPs are situated in a district; of which the district is situated in a region and country. Multiple WUs can use a single WP and multiple WUs and WPs can be situated in a district. However, only one DLA and GW entity can be situated in each district. DLAs and GW can both limit multiple WPs. DLAs can monitor GW levels and WPs use GW to serve WUs. Multiple districts can be situated in a region and multiple regions can be situated in a country. Regions and country influences how DLAs will perform SL in this model; while districts influence the amount of population, the number of WPs and surface areas of which WUs are allowed to be situated in.

Entities contain elements in the model as well, and these elements are the information agents will use to direct actions and influence states of the agent itself or other agents. Entities in the system each contain an identification to represent their identity. Each WU contains a different location to represent the user's home; and records of the amount of distance travelled to collect water, as well as the type and amount of water each WU has collected. Similar to WUs, each WP contains a unique location. WP can be either a safe type or unsafe type.

A safe type WP represents a hand pump constructed on top of a shallow well, and only this type of water supplying infrastructure was considered because the aim of this study was set to build upon Knipschild's (2016) work. Unsafe type WPs usually represents untreated, contaminated and open water sources. Insufficient data was available to the author at the time of the study on unsafe type water sources in Uganda; therefore, unsafe type water sources represent a river after expert consulting (Casella, n.d). There is a set number of litres allowed to be extracted at safe type WP, representing the effect of rationing at WPs. Since GW is used by safe type WPs and it is the technical limit in the STS, GW contains the total amount of GW a district contains. Unsafe WPs was designed to not have this limit, because according to the insight on Uganda's water cycle in chapter 1, there is an abundant amount of renewable surface water annually.

DLAs contain information about the GWs and ration ratios of its own district and other districts. Districts contain information about how many WUs and WPs are in their district, as well as the boundaries of the district. DLAs, regions and country each have a SL style for DLAs to follow, and the details of how SL was conceptualized in the model is explained in the next section.

5.3.2 Conceptualizing of social learning for the model

According to Knipschild (2016), modelling learning was done by the theory of memetics and evolution as it enables a modeller to encode learning into ABM; and due to time constraint, an assumption was made where Knipschild's way of modelling learning is sufficient for this study. Inspired by Knipschild, social learning was conceptualized under three separate processes for this study: selection, replication and variation.


District level authority	RationRatio	Groundwater Tank level
 ID	%	Remainder litres of water

Figure 6: Example of the meme content in the designed model

Meme: As explained in chapter 2, a meme is a unit of information. In the designed model, a meme contains GWL and the ration ratio used in the particular district. Figure 6 illustrates the contents of an example meme in the model.

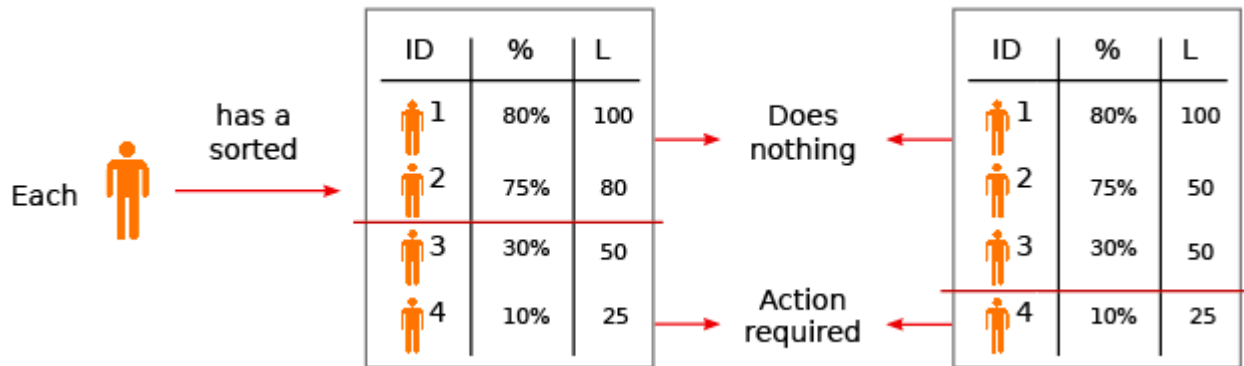


Figure 7: An illustration example of the selection process flow of a DLA in the designed model

Selection: As mentioned in the previous section, DLAs contain information about GWLs and ration ratios of its own district and other districts. DLAs assess the performances of other district's GWL against its own and rank districts in a descending manner. Inspired by Knipschild (2016), districts belonging in the lower half of the ranking list will select the highest ranked district to learn from. However, due to the assumption of learning agents were assumed to be always motivated and attentive to learn and apply what they have learned, the last district in the top half of the ranking list will also select and learn from the best ranking district; in order to reflect this assumption in the model. The halfway mark of the ranking list is always rounded down in the model. The selection process was assumed to occur as described above. Figure 7 is an example of the selection process a DLA in the model would undergo.

Replication: The memes of which DLAs will learn from and copy into the ranking list is done through the process of replication; and therefore, it is based on the different SL styles available in the designed model. Three different styles of SL were used in Knipschild's way of modelling learning; hence, the same styles was used in the model for this study. The three SL styles are: fully rational (FR), myopic and random. In FR, all DLAs are able to access GWL and ration ratios from all districts in the model. Under myopic, DLAs only get access to GWL and ration ratios from districts within the same region. DLAs can select the number of districts and which district(s) to learn from under random SL style. FR represents information is spread from the national level, where GWLs and ration ratios are published in an annual report. Myopic represents information is spread at a regional level, where only participating districts' representatives will get access to and share information. Associations in the WASH sector reflects myopic style of SL. Random SL style represents there are no structured way of information diffusion, and actors get access to information through meeting other representatives on their own or through other mediums. In order for these learning styles to function in the model, an assumption was made where DLAs have full information about their own GWLs and ration ratios at all times; because information is not always available or delayed in Uganda (Knipschild, 2016). Figure 8 illustrates how DLAs would construct their ranking lists in the model under the three SL style.

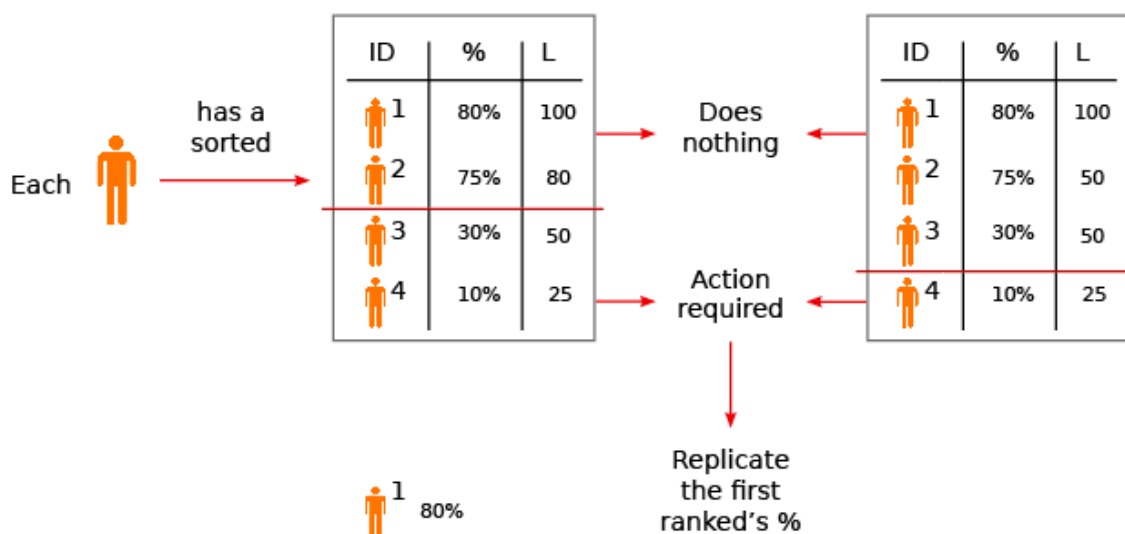


Figure 8: An illustration example of the replication process flow of a DLA in the designed model after the selection phase

Variation: The SL process includes interpreting what was learned and the ability to reproduce what was learned; therefore, DLAs can decide whether to apply a perfect copy of the ration ratio from the first ranked district, or a variation of the ratio. Variation in SL can represent a communication error, interpretation error, or adapting to the needs of the district (Knipschild, 2016). Diversity is an important element in SL, and variation could address this aspect in the model. Variation of the ratio is done by means of the random fractional method (Knipschild, 2016), where the learned ratio moves away or towards the DLA's original ratio by a random fraction. In the designed model, the variation process begins with calculating the absolute difference between the learned ratio and the DLA's own ratio. A random amount between zero and the absolute different is either added or subtracted randomly from the learned ratio. If the

ratio resulted in a value between 0 and 1, the DLA will learn and apply the product. If the ratio exceeds 1, the final ration ratio learned and applied by the DLA is set to 1. If the value drops below 0, the DLA will apply and learn the ration ratio from the first ranked district subtracted by a random value between 0 and the ratio value of the first ranked district. Figure 9 illustrates how variation is performed in the designed model.

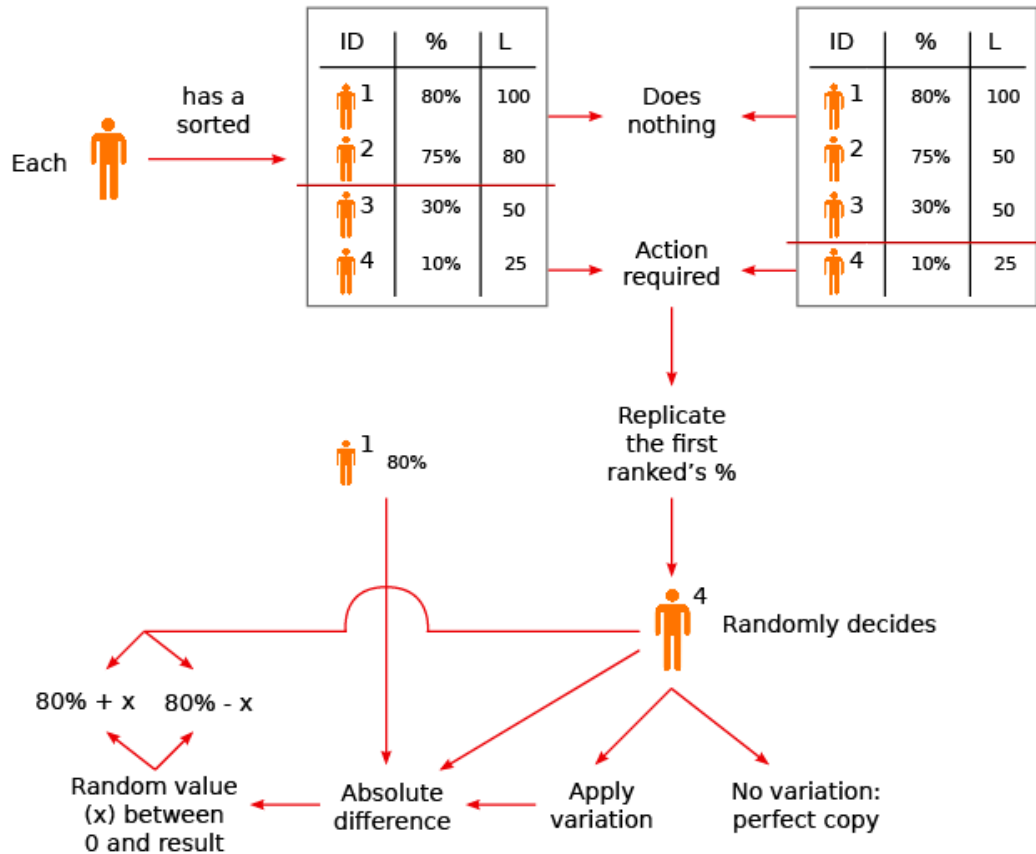


Figure 9: An illustration example of the variation process flow of a DLA in the designed model after the selection and replication phase

SL was conceptualized for the ABM in this section using the concepts of meme, selection, variation and replication explained in this section. In the next section, details of the ABM parametrization will be discussed.

5.4 ABM parametrization

As introduced in section 5.1, the three components of an ABM are: agents, environment and time. In this section, the conceptualizations from the previous section are translated into design details of the model and are categorized into the three components. Section 5.4.1 will describe the agents included in the model, and the environment and time will be described in section 5.4.2.

5.4.1 Agent parametrization

There are five different types of agents in the model, namely DLA, WU, WP, GWL and district. These agents represent the conceptualizations of the RWSD STS in Uganda; with the exception of region and country which are represented in the environment and will be described in the next section. This aim of this section is to describe the properties each agent contains, the purpose of designing those properties into each agent, the interactions between these agents and how will each agent decide which actions to take under different conditions.

5.4.1a Water user agent

The water user agent represents residents in the rural areas of Uganda who make use of hand pumps at shallow wells and contains the following variables:

- CumulativeTravelledDistance: Contains an integer value which indicates how far the WU have traveled to collect their desired amount of water per tick
- WU ID: Contains an integer type value which represents the ID of the WU agent
- WUDistrictBelongTo: Contains an integer type value indicating which district the WU agent belongs to
- TotalSafeWaterCollected: Contains an integer which indicates how much water did the WU agent collect from a safe type WP in total over the course of the simulation
- SafeWaterCollected: Contains an integer which indicates how much water did the WU agent collect from a safe type WP from the current tick
- TotalUnsafeWaterCollected: Contains an integer which indicates how much water did the WU agent collect from an unsafe type WP in total over the course of the simulation
- UnsafeWaterCollected: Contains an integer which indicates how much water did the WU agent collect from an unsafe type WP from the current tick
- Location: Contains the location of the actual WU agent described in x and y axis
- WPSafeList: A list which contains information about all the safe type WP in the district, and each item represents one WP in the district. Each item contains information about the name of the WP, location of the WP, and the calculated distance between the WP and the WU's current position.
- WPUnsafeList: A list which contains information about all the unsafe type WP in the district, and each item represents one WP in the district. Each item contains information about the name of the WP, location of the WP, and the calculated distance between the WP and the WU's current position.

5.4.1b Water point agent

The water point agent represents hand pumps at shallow wells in the rural areas of Uganda of which water users in rural Uganda uses, and contains the following variables:

- Location: Contains the location of the actual WP agent described in x and y axis **The exact geographical characteristics in rural areas of Uganda is not modelled, but rather using a random location placement for WPs to represent the different geographical characteristics in each district. This does not include the pathway that the WU will

travel in the model, but rather where would be applicable for the WP to be installed or those unsafe water sources would appear.

- Type of WP: Contains an Boolean value which represents the type of WP the agent is (improved source or unsafe source)
- LitresAllowed: Contains an integer value which represents the amount of water the water point agent is allowed to serve WUs in their district per tick of the simulation in liters
- LitresExpected: Contains an integer value which represents the the amount of water the WP is expected to serve in liters, from the amount of WUs which will choose this particular WP agent as their first water collection choice
- WP ID: Contains an integer type value which represents the ID of the GWL agent
- WPDistrictBelongTo: Contains an integer type value indicating which district the WP agent belongs to

5.4.1c DLA agent

The DLA agent represents governmental representatives from the national government of local governments, institutions or organizations. DLA agents learn, apply or variate ration ratios; and contains the following variables:

- Location: Contains the location of the actual DLA agent described in x and y axis
- Ration ratio: Contains a float type value used for GW rationing by applying it to WPs
- DLA ID: Contains an integer type value which represents the ID of the DLA agent
- LearningList: A list which contains the information of other DLA agents in other districts, their rations, GWLs, and region for SL
- DLARegionBelongTo: Contains an integer type value indicating which region the DLA agent belongs to
- DLADistrictBelongTo: Contains an integer type value indicating which district the DLA agent belongs to

5.4.1d GWL agent

The GWL agent is a representation of GW resources in Uganda per district, and contains the following variables:

- Location: Contains the location of the actual GWL agent described in x and y axis
- GWL ID: Contains an integer type value which represents the ID of the GWL agent
- WaterAmount: Contains an integer type value which represents the amount of water left in the modeled GW reserves in Liters
- GWLDistrictBelongTo: Contains an integer type value indicating which district the GWL agent belongs to

5.4.1e District agent

District agents represent the surface area of a district in Uganda, and contains the following variables:

- GridList : A list which contains the coordinates of the 4 corners of the district space on the model map
- Number of population: Contains an integer type value indicating the number of WUs in the district
- Number of WP: Contains an integer type value indicating the number of WPs in the district
- District ID: Contains an integer type value which represents the ID of the district agent
- Location: Contains the location of the actual district agent described in x and y axis
- WUList: contains all of the WUID in their district
- WPList: contains all of the WPID in their district
- DistrictBelongToRegion: contains the region ID of which the district belongs to

5.4.1f Agent interactions

After knowing who and what is included in the model, their main designed actions and interactions could be mapped out next using an action sequence diagram (Figure 10) to show what will happen, when will these (inter)actions take place and which agents are interacting in the model.

There are five agents in the model: District, GWL (GW agent), DLA (District level authorities agent), WU (water user agent) and WP (water point agent). The horizontal arrow lines represent outward signals from the agent initiated the interaction towards the signal receiving the signal. The horizontal dashed lines represent feedback or response from the signal receiving agent towards the signal sending agent. The vertical dashed lines represent the specific agent type and the vertical colour-filled boxes represent an (inter)action.

The district agents will first setup a district space and distribute the location space to other agents. The agents will use this information to place themselves in the model. After the locations are set, the WU agents will request the location of all of the WPs in their own district and make a list from it. The WPs will also request the location of all of the WUs in their own district, then calculate how many WU agents will collect water at the WP agent's location. Based on the results of the calculation, the WP agent will generate the amount of water expected to serve. DLA agents will send their own ration ratios to the WP agents in their own district and the WPs will apply the ration ratio and adjust the litres of water allowed to serve. The above mentioned actions are the overall interactions between the agents during the setup of the model simulation.

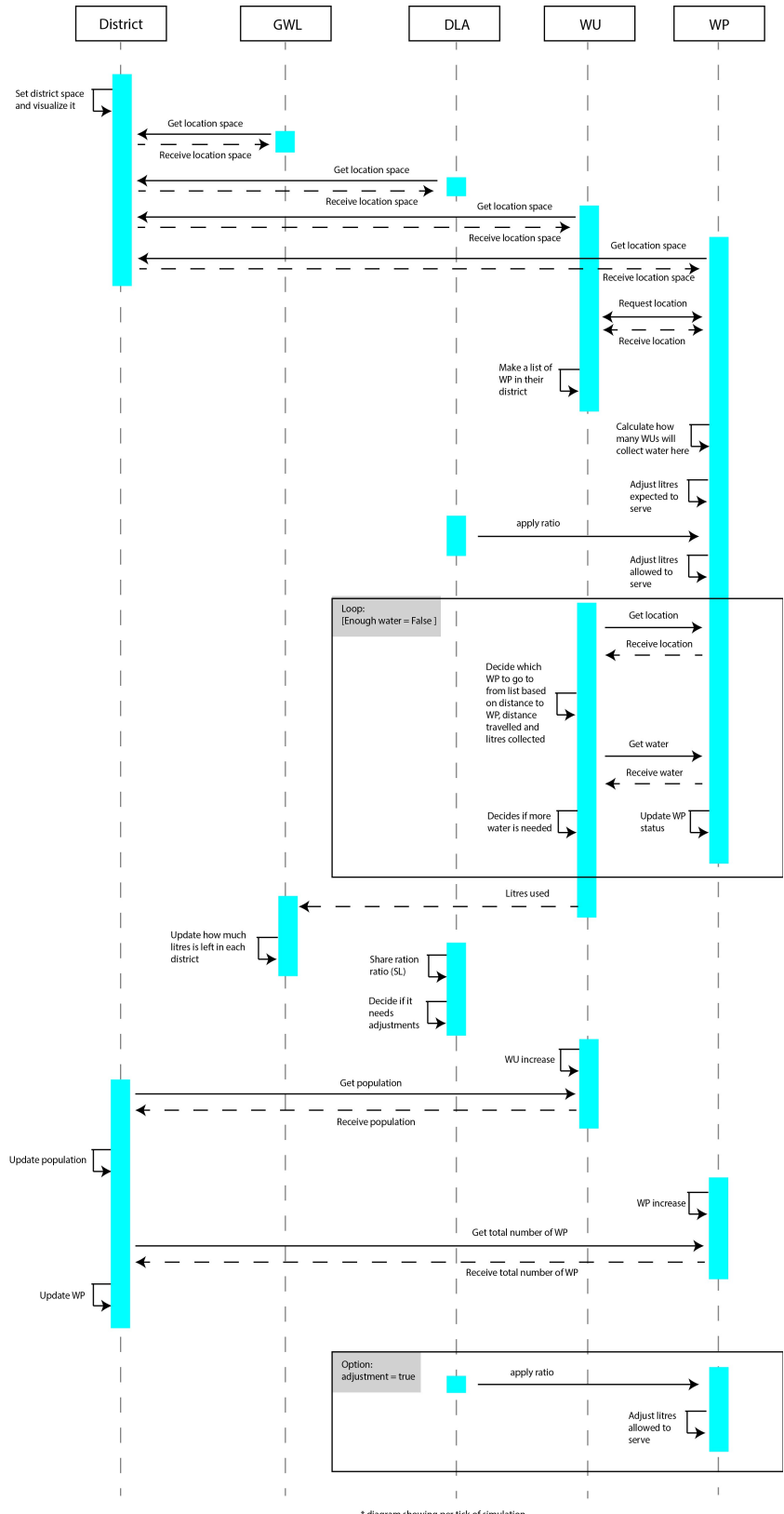


Figure 10: action sequence diagram of the designed model

During the simulation, WU agents will first enter a loop which repeats the interaction between WP and WU until the WU agent collected enough water. The WU agent will gather information about the WP agents in their own district first within the loop, then decide which WP to visit for water extraction based on its own travelled distance, distance to the next WP agent and the amount of water collected. The WP agent will update its own information after interacting with the visited WU agent. The WU agents will update the information with the GWL agent within their district about how much water was collected. Afterwards, DLA agents interact with each other to share ration ratio and decides if their own ration ratio needs adjustments. New WU and WP agents are created with the district agent following the sharing of ration ratios. Lastly, if adjustments are needed, the ratio will be applied to the WP agents in their own district and WP agents will adjust their water serving allowance. The above mentioned actions in this paragraph are repeated until the simulation is over.

The agents along with their variables and interaction included in the designed model were described and explained in this section. In the next section, an explanation on the remaining designed ABM core components (environment and time) will be given.

5.5 Environment and time parametrization

As mentioned in the previous section of this chapter, ABM consist of three core components, namely agents, environment and time. In the previous section, the agent component of the designed model was described; and therefore an explanation on the designed model environment and time will be given in sections 5.4.2a and 5.4.2b respectively.

5.5.1 Environment parametrization

The environment is the space of which agents exist, act and interact with each other in an ABM (Knipschild, 2016). It contains everything that affects agents, except the particular agent itself (Dam, Nikolic & Lukszo, 2013). Hence, the following variables were included in the environment of the ABM within the design context.

- *PopulationGrowthRate*: A value slider variable to control how many WU type agents will be placed in each district after each tick during the simulation.
- *WPGrowthRate*: A value slider variable to control how much WP type agents will be placed in each district after each tick during the simulation.
- *NumberWUPerDistrictToStart*: A value slider variable to control how many WU agents are situated in each district at the beginning of the simulation, and it was set to have a value of 10 because of assumption 5.
- *NumberWPPERDistrictToStart*: A value slider variable to control how many WP agents are situated in each district at the beginning of the simulation, and it was set to have a value of 5 because of assumption 5.
- *NumberDistrictsToStart*: A value slider variable to control how many district agents are situated in the model at the beginning of the simulation, and it was set to have a value of 12 because of assumption 5.
- *ModelDuration*: A chooser variable to control how many ticks the simulation will run

- SLStyle: A value slider variable in the model to control the type of SL DLA breed agents will be using in the simulation

Since DLA agents were assumed to have the power to control extraction flows and are representatives from the national level, agents of this type do not have the power to control the SL style the entire nation will perform. Therefore, SL style was designed to be part of the model environment and thus the national level of Uganda is represented. Global variables in the model also interact with agents, and the global variables designed in the model were as follows:

- ReportingSheet: a global list variable which stores the information agents report for data result export
- Year: an integer variable which stores the current tick of the simulation and agents use this value when reporting to the variable ReportingSheet

The environment component of the designed ABM was described in this section; the explanation continues on with the last component in the next section. The time component of the designed ABM will be explained and described.

5.5.2 Time parametrization

Time is the third component in the anatomy of an ABM (Knipschild, 2016). Discrete time is used in ABM and the smallest unit of time is represented by a tick (Dam, Nikolic & Lukszo, 2013). A tick can be redefined by the designer to represent different length of time (Dam, Nikolic & Lukszo, 2013). A tick in the designed ABM represents a year in real time for this study.

Time parametrization also includes the design of procedures the model will perform from the beginning of the simulation until the end of the simulation. In other words, the procedures agents will perform in each year in the model. The explanation of the procedures begins with a list of the functions made for the model to execute shown in the designed execution order, followed by a description of what each function does in the model.

- Simulation termination check step: Checks if the run time of the simulation reached the model duration set from the remote. Terminates the model if the run time has reached the pre-set duration.
- WU water collection step: Water users visits the WPs within their district and collect the desired amount of water.
- GWL update step: Updates the amount of water left in the agent itself based on the amount of water collected by WUs in their district.
- UpdateReportingSheet: In preparation for the model data result output, agents in the model report and stores their variable information in the ReportingSheet global variable list every tick in this function.
- DLA social learning step: DLAs in the model exchanges GWL and ration ratios information with each other according to the pre-set SL type for the simulation.
- DLA decision step: DLAs decide whether or not to learn or variate the ration ratios

- WU-variableClear step: WU type agents empty their WPSafeList and WPUnsafeList and replace their SafeWaterCollected, UnsafeWaterCollected and CumulativeTravelledDistance variable values to 0.
- Population increase step: Increase the amount of WUs in all districts by the amount set in the controllers.
- WP increase step: Increase the amount of safe type WUs in all districts by the amount set in the controllers.
- DLA ration ratio application step: DLAs apply ration ratios to WPs in their district
- Data Output step: Gather GWL, ration ratios, each district's water collection profile and cumulative travelled distance of WUs, put the results into a list per tick and report the list.

Simulation termination check step: The global variable Year will be increased by 1 and checked against the value from global variable ModelDuration, if the difference between the two is zero, the simulation terminates and represents the preset ModelDuration amount of years have past in the model.

DLA social learning step: DLA shares their GWL between districts based on SLStyle type in this step. A separate temporary list is created and all DLA and GWL type agents will store their DLA ID, DLADistrictBelongTo, RationRatio and GWL as an item in the list. The list is created by first asking all DLA agents to add their information in the temporary list first, then ask each GWL agent to check whether the DLADistrictBelongTo value matches with GWLDistrictBelongTo. The GWL agent will store its GWL information in the respective DLA agent item slot accordingly.

If the SLStyle type is FR, the temporary list will be sorted based on GWLs with the highest value on the top of the list. All DLA breed agents will copy the temporary list into their own DLA list afterwards. The DLA agent will rank each item on the list based on their respective GWLs.

If the SLStyle type is myopic, ask DLA agents to only copy the items on the temporary list to its own DLAList, when the region value matches with the DLA agent's DLARegionBelongTo stored value. The DLAList will be sorted again based on highest GWL value. The DLA agent will rank each item on the list based on their respective GWLs.

If the SLStyle type is random, each DLA agent will first roll a number between 0 and 12 to determine how many random items will it copy, then roll again for which item on the temporary list it will copy. The DLA agent will copy those items from the temporary list into their own DLAList and sort them based on GWLs, with the highest value being at the top of the list. There is a probability where the DLA agent will copy the same information twice, therefore it will also check its own list and remove any redundant entries. DLA agents cannot learn from itself and count towards a learning instance under random SLStyle as well, because each learning list already contains the meme from itself. Learning will repeat until a meme from a different DLA agent is learned. The DLA agent will rank each item on the list based on their respective GWLs.

DLA decision step: Each DLA will first locate themselves in the DLAList and the rank they are placed in their own list. Next, the DLA agent will store the best ranking ratio on the DLAList in preparation for learning. If the DLA agent is ranked lower than 50% on the list, the DLA agent will decide to act on it. The DLA agent will copy the ration ratio from the district ranking first on the list. A random dice roll between 0.0 to 1.0 determines (condition for variation is > 0.5) if the copied ratio will be slightly adjusted for variation. If the dice roll fails to meeting the preset condition, the DLA agent will replace its own ration ratio with the copied ratio right away. If the dice roll results in a number of which the preset condition could be met, another dice roll will determine whether the copied ratio will increase or decrease in comparison to the ratio it wants to copy. The amount it will adjust is a random number between 0 and the difference between the desired ratio and the original ratio. After the adjustments, the copied ratio will replace the DLA agent's starting ratio for this step. Learning of the ratio will not take place if the DLA agent's rank is placed within the top 50% of the list, at exactly 50%, or when the list only contain its own ratio.

DLA ration ratio application step: DLA applies the ratio to all safe WPs in their district. Each safe WP will recalculate how much litres it is allowed to serve by executing the UpdateLitresExpected and the UpdateLitresAllowedWithRatio functions. The explanations of these functions can be found in the set-up section of the model narrative.

ALLWU-UpdateWPList: This function updates all of the WU's unsafe type WP list and improved WP type list. Each item on these lists contain the IDs of the WPs in their district in their respective type and the distance between the WU and WP in one-way trip manner. This function is used within the WU Collection Step function.

CheckLitresDesired step: This is a function where the WU's desired litres are set based on the sum of the distance they have travelled, the travelling distance between the WU's current position and the intended WP the WU is travelling to, and from the WP back to the WU's original starting position. If the total distance is less than 1.50km, the WU will desire to collect 20L; otherwise the WU will be set to desire collecting 10L. This function is called in the WU Collection Step function.

WU water collection step: Each WU will create a separate temporary list where they'll combine their safe and unsafe WP lists together, with all of the safe WPs first on the list before continue adding the unsafe WPs in the list. The temporary list will not be sorted again based on distance. The list contain the ID of WPs, Location of WP, the distance between the WP and the WU's current position.

A counter variable named LitresCollected is created to keep track of how many litres of water the WU agent has collected, as well as a condition variable named LitresDesired to represent how many litres of water does the WU agent wants to collect from the WPs. A temporary variable is created to store the current position of the WU and will be set to the WU's original position here. While the value set inside of LitresCollected is not bigger or equal to LitresDesired, the WU agent will keep executing the following instructions until the condition is met.

The WU will first update the variable LitresDesired using the CheckLitresDesired function; if LitresCollected is equal or greater than LitresDesired, the WU will stop collecting water and breaks out of this function. If LitresDesired less than ListresCollected, it will check the first item on the temporary list for the WP's, then check what WP type is the WP agent.

If the WP is a safe type, the WU agent will check if the WP agent could serve water. If the WP cannot serve anymore water, the WUs will add the distance it travelled from its current position to the WP to its CumulativeTravelledDistance variable counter. The temporary position variable is updated to the position of the WP and the distance between the current position of the WU and all of the WPs in the temporary list is updated. It is because the WP of which the WU is visiting is always the first item on the temporary WP list, the first item will be removed. The list is sorted based on the distance between the WU's current position and other WPs in the district in a descending order regardless of the type of WP afterwards.

If the WP could serve more water, the WU will check if the WP can sufficiently supply the desired amount of water to be collected. If the WP could sufficiently supply the amount of water the WU is requesting to collect, the WP will replace its LitersAllowed variable value with the difference between LitresAllowed and LitersDesired. The temporary position variable is updated to the position of the WP. The value stored inside LitresDesired will be added to both the WU's TotalSafeWaterCollected and SafeWaterCollected variable. LitresCollected will be updated to the sum of the amount it originally had with the difference between LitresDesired and LitresCollected as well in order for the WU to break out of the function. The WUs will also add the distance it travelled from its current position to the WP to its CumulativeTravelledDistance variable counter.

If the WP could serve water but does not have enough water quota left to satisfy the amount of litres the WU is seeking for, LitresCollected will add the remainder litres of water the WP agent has to to itself, and change the status of the WP agent from serving to closed for the this simulation tick by changing the variable LitresAllowed to zero. The temporary position variable is updated to the position of the WP and the distance between the current position of the WU and all of the WPs in the temporary list is updated. The WU will update its TotalSafeWaterCollected and SafeWaterCollected variable by adding LitresAllowed to both variables. The first item on the temporary list is removed and the list is sorted based on distance regardless of WP type. The WUs will add the distance it travelled from its current position to the WP to its CumulativeTravelledDistance variable counter.

If the WP is an unsafe type, the distance travelled by the WU will be added to WU's CumulativeTravelledDistance variable update its current position. The amount of LitresDesired is collected and the variable LitresCollected, UnsafeCollected and TotalUnsafeCollected variable are updated.

After breaking out of the loop and before breaking out of the function, the returning distance between the current position and the WU's original position is added to the CumulativeTravelledDistance variable.

Population increase step: New WU agents are placed in each district according to the global variable value of PopulationGrowthRate. The value of population in the district agent

will change for district type agents, as well as new WUs will be added in the model. If the number of new WU agents placed in the district is above 110, no new WUs will be added to the district.

WP increase step: New improved type WPs are created in each district during this phase. The amount of WP increase in this step depends on the global variable of WPGrowthRate. The district type agents' WPList will be updated accordingly.

GWL update step: All GWL agents will update their tank levels (WaterAmount variable) by visiting each WU agent in their own district and subtracting its WaterAmount variable value with the WU's SafeWaterCollected. A random percentage of the water collected from the unsafe sources will be contributed to the subtraction of WaterAmount to represent unsafe sources which are GW based due to the insufficient information on unsafe sources in Uganda at the time of this study.

WU-VariableClear: Each WU will clear their WPSafeList, WPUUnsafeList, SafeWaterCollected, UnsafeWaterCollected and CumulativeTravelled distance variables in preparation for the next simulation tick.

Simulation time update step: Global variable Year is updated by adding one to the variable to represent a year has past. If the global variable value ModelDuration is equal to Year, the simulation terminates.

UpdateReportingSheet: This function updates the global variable ReportingSheet. Values from Year, GWL, DLA and WU agents are translated into an item and stored into a list. Each item represents information from each district and their GW level (WaterAmount from the corresponding GWL agent), ration ratio (RationRation from the corresponding DLA agent) and the CumulativeTravelledDistance along with their water collection portfolios from all of the WUs in the district. Water collection portfolios are calculated as the amount of water collected from an improved type WP divided by the total amount of water collected regardless of water type. Due to computational time limitation, the water portfolios and cumulative travelled distance are sorted into categories for data export. The categories for water portfolios are: 0% - 9.99%, 10% - 19.99%, 20% - 29.99%, 30% - 39.99%, 40% - 49.99%, 50% - 59.99%, 60% - 69.99%, 70% - 79.99%, 80% - 89.99%, 90% - 99.99% and 100%. The categories for cumulative travelled distance are: 0 km - 0.49 km, 0.5km - 0.99 km, 1 km - 1.49 km, 1.5 km - 1.99 km, 2.0 km - 2.49 km, 2.5 km - 2.99 km and 3km or above.

DataOutput: This function is called at the end of the simulation to report and export the global variable ReportingSheet, which is the result from the UpdateReportingSheet function.

From the previous sections in this chapter, SL for GW resource management under the RWSD STS in Uganda was conceptualized and translated into functions, variables, agents, environment, and time components for agent based modelling. In other words, steps 2 to step 4 of the ABM practice guideline was followed. The model was implemented as the next step in the ABM practice guideline and the product of the implementation will be shown in the next section.

5.6 ABM implementation

The agent based model was implemented in a computer software according to the conceptualizations and translations described in the previous section. The computer software was used for the model implementation for this study was Netlogo. The full details of how the model was designed and encoded into Netlogo was explained using a model narrative and Pseudo code; while parts of the model narrative was used in the previous section, the full version of the narrative is located in Appendix I. The Pseudo code translates the model narrative from the previous section into a description of what the computer simulation program must do. The pseudo code is the last step before the simulation is created in the Netlogo environment (Knipschild, 2016), and the Pseudo code made for the designed model is located in Appendix J. Figure 11 is a screenshot of the model and its interface.

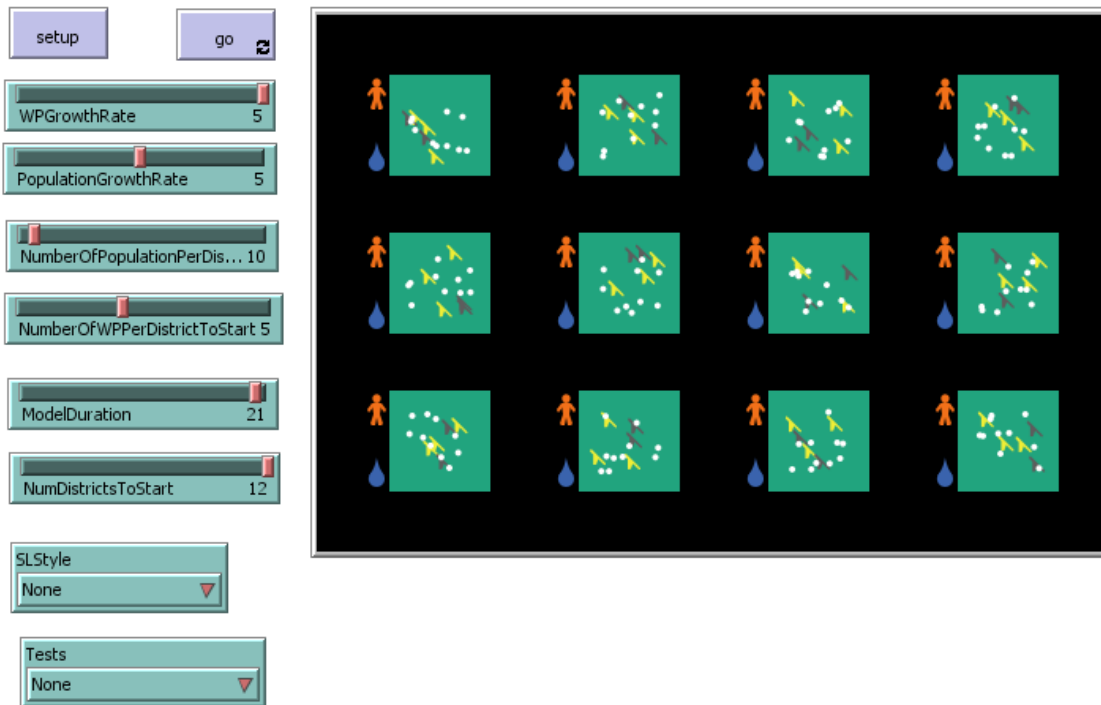


Figure 11: screenshot of the model and its interface

There are two buttons, six sliders and two choosers in the model's controllers interface, and each one represents a variable in the environment component of the ABM. This is shown on the left side in Figure 11. The setup button performs the designed set up procedures in preparation for the simulation. This includes placing district agents, WU agents, WP agents, DLA agents and GWL agents on screen at the right position; and inserting the agent specific variables along with the corresponding values at the start of the simulation. The go button performs the procedures set up to be performed at each tick and to repeat those procedures until the stopping condition is met. The environmental variables of the ABM are controlled using integer value sliders and a chooser; the variables are: the amount of new WUs placed in each district every year (PopulationGrowthRate), the amount of new WPs placed in each district every year (WPGrowthRate), starting amount of WU and WP in each district

(NumberOfPopulationPerDistrictToStart, NumberOfWPPERDistrictToStart), the amount of districts in the simulation (NumDistrictToStart) and SL style (SLStyle). The chooser for SL Style contains three options for selection, namely FR, myopic and random. The last chooser designed in the interface was named Tests, and it contains nine options for selection. Each item on the selection represents a designed test for the model to execute for the verification phase of the ABM practice procedure. The design of the Tests chooser was for the convenience of the designer to run different tests to ensure the model was functioning correctly. The nine tests options were named: Test1, Test2, Test3, Test4, Test5, Test6, Test7, Test8, Test 9 and none. The designed specifications of the tests will be shown along with the test results in section 5.7 of this chapter.

Apart from the controllers, visualizations of the model simulation was also included in the model interface. This is shown on the right side in Figure 11. There are twelve districts in the simulation model, represented by the teal colour filled squares in the model and were organized in a three rows by four columns fashion. Each row within the visualized simulation represents a region, and there are a total of three regions. The DLA agent is represented by the orange colour filled humanoid silhouette located near the top left corner of each district. The GWL agent is represented by the blue colour filled water drop symbol located near the bottom left corner of each district. WUs are represented by white colour filled ovals located within the teal colour filled squares. The slanted T-shaped symbol represents WPs within the districts and are located within the teal colour filled squares. The black colour filled T-shapes represents unsafe type WPs, while the yellow colour filled T-shapes represents improved source type WP.

From this section, the ABM implemented in the Netlogo software environment for this study was explained. According to the ABM practice guideline, the fifth step was completed and model verification is the next step, which will be explained in the next section.

5.7 ABM verification

Model verification was executed as the sixth step of the ABM practice to ensure the designed model was designed, encoded and functioned properly into the software environment. A total of nine tests were designed and performed to prove the implemented ABM was indeed functioning correctly. In this section, the specifications of each test will be given along with their tested results.

The verification tests were made according to the ABM practice guideline by Dam, Nikolic & Lukszo (2013). In order to verify the model, the simulation tests were performed in a predictable environment in contrast to the default settings of the model; which was designed to operate in an unpredictable environment. The outcomes of the simulation were predicted according to different sets of predefined inputs before the execution of the tests, and the outcomes were compared against the outcomes after the simulation tests. There were two different types of tests conducted in the verification phase of this study, namely single agent tests and minimal interaction tests. In single agent tests, the performance of a single agent is observed and verified under the testing conditions; and in minimal interaction tests, at least one of each agent type is included in the model. Due to the nature of the designed model, the tests were all set up to be minimal interaction tests, because the agents were designed to

operate in dependence of other agents. However, several tests were designed to explore the behaviour of a single agent. Each test was encoded into the programmed script, and the model displayed different responses according to the results in the command centre of the Netlogo environment. If the simulation result matches with the predicted outcome, a positive response was programmed to display in the command centre; while a display of a negative response or an empty response indicates the outcome did not match with the predicted outcome.

A total of nine tests were made to verify the model. The criteria and results of each test is briefly explained in Table 2.

Test #	What was tested	Result
1	WU water collection behavior: when an improved type WP is located within a travelling distance of 1.5km and an unsafe type WP is located further away.	Passed
2	WU water collection behavior: when an unsafe type WP is located within a travelling distance of 1.5km and an improved type WP is located further away.	Passed
3	WU water collection behavior: when an improved type WP is located within a travelling distance of 1.5km reached the maximum extraction capacity and an unsafe type WP is located further away.	Passed
4	WU water collection behavior: when an improved type WP is located within a travelling distance of 1.5km reached the maximum extraction capacity and an unsafe type WP is located further away. A new improved type WP agent is inserted at a location furthest away from the WU agent.	Passed
5	Model environment conditions do not exceed the limits of the model at the beginning and during the simulation.	Passed
6	Social learning: The aim of this test was to verify if DLA agents learn and apply ration ratios properly under the FR SL style	Passed
7	Social learning: The aim of this test was to verify if DLA agents learn and apply ration ratios properly under the myopic SL style	Passed
8	Social learning: The aim of this test was to verify if DLA agents learn and apply ration ratios properly under the random SL style	Passed
9	Social learning: variation of ration ratios after learning	Passed

Table 2: Model verification test criteria and results

The model passed all nine tests as shown in Table 2. The full details of the model verification tests and results can be found in Appendix K. From this chapter, the designed ABM was described according to the context of this study; and was proven to be functioning correctly to the best of the author's ability from the performed tests in this section. According to the ABM practice guidelines, steps 1 to 6 was executed; and the main research question of how to

conceptualize and model social learning for GW rationing in rural areas of Uganda for domestic use was primarily addressed through the designed ABM. However, the ABM practice guideline contains four additional steps after model verification. Experimentation, the immediate step after model verification was taken place and will be explained in the next chapter of this thesis report.

6. Experimentation

After conceptualizing, constructing and verifying the ABM, experimentation was possible using the designed model. Experimentation in this study means the model was applied to a study case of interest; where model simulations were executed based on a set of parameters determined in relation to the study of interest. Besides being the seventh step in the ABM practice guideline, experimentation was used to explore the limits of the model itself and to utilize the device created by the author to explore in the research direction set out earlier in chapter 1.

In chapter 1, the proposed ideal main research question was to investigate the effects of GW levels, based on the application of SL in the domain of both GWL management and WSL improvement concurrently was discussed. Although, the scope in the proposed main research question was unsuitable for this study, the designed model could serve as an investigative attempt to study a small section in this ideal direction.

Since the model was designed to have GWLs management working independently from WSLs improvement, applying the designed model to study how GWLs and WSLs would react under the effects of SL and GW resource management was the area of interest selected for insights gathering. In order to gain insights within the area of interest using the designed model, appropriately designed experiments were required (Dam, Nikolic & Lukszo, 2013); and this includes a set of questions aimed at the area of interest, experiment design specifications and hypothesis of the experiment outcomes. The questions of interest for this experimentation were:

EDQ1: Would a pattern about GWLs and WSL emerge from different SL diffusion for GW rationing?

EDQ2: How would the GWL (overall system) and WSL (internal system) behave under SL influence for GW management?

The insights gained from answering the above mentioned questions can help decision makers in policy and decision making in Uganda's WASH sector; and contribute to the research community in the ideal research direction. In section 6.1, the design specifications of the experiment is presented. The hypothesis of the experiment outcomes is described in section 6.2. A summary of the designed experiment is given in section 6.3.

6.1 Experimental specifications

The application of the model assisted in answering the two questions listed above by running the model in different conditions and also known as the specifications of the experiment. A full factorial parameter sweep was selected for the experiment. The parameters selected for the sweep were WP growth (WPG), population growth (PopG) and SL style; because WP growth and population growth could generate data in order to answer EQ3, and EQ1 could be answered through the data generated under different SL style settings in the designed model.

		WP growth							WP growth							WP growth					
FR		1	2	3	4	5	M		1	2	3	4	5	Pop growth		R	1	2	3	4	5
Pop growth	1	1,1	1,2	1,3	1,4	1,5	Pop growth	1	1,1	1,2	1,3	1,4	1,5	Pop growth	1	1,1	1,2	1,3	1,4	1,5	
	2	2,1	2,2	2,3	2,4	2,5		2	2,1	2,2	2,3	2,4	2,5		2	2,1	2,2	2,3	2,4	2,5	
	3	3,1	3,2	3,3	3,4	3,5		3	3,1	3,2	3,3	3,4	3,5		3	3,1	3,2	3,3	3,4	3,5	
	4	4,1	4,2	4,3	4,4	4,5		4	4,1	4,2	4,3	4,4	4,5		4	4,1	4,2	4,3	4,4	4,5	
	5	5,1	5,2	5,3	5,4	5,5		5	5,1	5,2	5,3	5,4	5,5		5	5,1	5,2	5,3	5,4	5,5	

Figure 12: All simulation combinations for the experiment

The districts in the model were designed to have a maximum WU capacity of one hundred and ten, and the model duration set at the maximum of 20 years; therefore the maximum population growth setting for the experiment was set to a value of 5 to avoid districts operating at maximum capacity at the early stages of the simulation. Avoiding maximum WU capacity at the early stages of the simulation was needed because the context of the study was set at the rural areas of Uganda; which means the majority of the experiments should not contain districts operating at full capacity. Limitations on the amount of maximum WP were excluded in the designed model; however, the range of WP growth values were set to be identical to population growth rate in the experiment in order to reduce computational time and to observe the behaviour when WP grows at the same or different rates. The three SL styles were required to observe how GWL and WSL changes alongside the population and WP growth rates; therefore, seventy-five simulation runs under different settings were required for the experiment. Figure 12 shows the seventy-five simulation settings for the experiment. The seventy-five combinations should be repeated in order to generate reliable data. Due to time constraint, 10 repetitions of each combination was designed into this experiment; which yields a total of 750 runs for the experiment. The remaining model controllers were set to the default settings of the model throughout the experimentation and were predefined as follows:

Model controllers	Selected value
NumberOfWPPERDistrictToStart	5
NumberOfPopulationPerDistrictToStart	10
NumDistrictToStart	12
ModelDuration	20
Tests	none

Table 3: Predefined model controller values for the experiment

The predefined values set for this experiment was according to assumption 5 and 32 in Appendix H of this report. After designing the inputs of the experiment, the outputs were designed in order to ensure the model output generates the correct type of data for observation. GWL was selected to become the common metric being observed from the output of the simulation runs because GWLs is the common connected area of interest where SL, WPs increase and population increase intersect. This corresponds with the theoretical perspectives chosen for this study, STS with environmental limitation. This is because the

area of concern for this study was about how the social and technical system respond to the environmental limitation; where the experiment resonates with this in terms of representing the changes in the social system from SL types and the technical system with WP increase and population increase. It was also because the questions of which the designed experiment was aimed to focus on GWL as well; and therefore, the overall system behaviour was observed through the results of GWLs.

Ration ratios, district ID region ID, simulation tick, cumulative travelled distance and water collection portfolios were the other outputs required apart from the GWLs from each district. District ID, region ID and simulation tick were required to identify and observe the time and place of which the behaviour occurred. Ration ratios were needed to observe how each SL style, population growth rates and WP growth rates affected rationing and WSL behaviour. In order to observe the internal behaviour of the designed system, cumulative travelled distance and water collection portfolios were also required in the outputs of the experiment as WSL elements. In addition to the above mention outputs, the input values of the experiment was included into the output of the experiment in order to organize the results under the different designed conditions of the experiment. As mentioned in section 5.5.2, the model output was designed to be a list containing different items; therefore, each item on the list was designed to represent the output of a district per year. In this section, the model specifications for the proposed experiment were discussed. In the next section, the hypothesis of the experimental outcomes will be described.

6.2 Hypothesis of the experimental outcomes

The last item required for a designed experiment was the hypothesis of the experiment outcomes. The hypothesis made for the experiment was as follows:

Under the modelled circumstances, a pattern would emerge because DLA agents would apply different ration ratios based on the different model environment. Since DLA agents would receive ration ratios from all of the DLA agents in the model under FR SL type, the overall GWLs would result in the highest. This is because all DLA agents would get exposed to other ration ratios in the selection process and therefore increasing the exposure of the “best” meme to other districts in the model. As a result, the overall results would be the highest as districts are improving their GWLs using the “best” meme.

Although the amount of districts affected by the best meme would be similar between FR and myopic, myopic limits the amount of districts getting in contact of the best meme overall; therefore, the FR type sets of experiments would perform better than myopic. Since the area of effect of the “best” meme and the access to the amount of meme fluctuates for each district under random type SL, myopic type experiments were hypothesized to perform better than the random type.

Ratio ratios were hypothesized to decrease overtime for all experiments because DLA agents in lower ranks were designed to learn and apply ration ratios continuously from the “best” performing district. The cumulative travelled distance of WUs would increase as ration ratios decrease; because WUs would need to travel to multiple WPs to collect the amount of water desired. WUs would collect more water from the unsafe sources as ration ratios decrease as

well; because the probability of WUs visiting another WP to gather water is higher due to the restriction and therefore leading to a higher probability of visiting an unsafe type WP in the collection process. As population growth rate increases, GWL depletion rates increases due to the increasing demand and no GW recharge in the model. As WP growth rate increases, GWL depletion rates increases as well due to the amount of access points WUs could extract water from increases.

From this section, the hypothesis of the experimental outcome was described and explained. In the next section, a summary of this chapter is given.

6.3 Experimental design summary

From this chapter, step 7 of the ABM practice guideline was addressed through the descriptions of the designed experiment for this study. Questions were generated to gain insights from the use of the designed model, hypothesis of the experiment outcome was made and model specifications were tailored to the needs of the experiment. Table 4 was made to summarize the content of the designed experiment.

Experimental design	Why?	Experimental Results	Why?
Full factorial parameter sweep: FR, Myopic, Random, model controllers set according to Table 3, 10 repetitions per experiment, 750 runs in total	See section 6.1	Not available	Not available
Would a pattern about GWLs and WSL emerge from different SL diffusion for GW rationing? - Hypothesis: Yes	Because of the changing environment in the model	Not available	Not available
Hypothesis of the overall system (GWL performance) behavior: FR > Myopic > Random	FR: All districts have access to the "best" meme Myopic: contains the same number of districts affected as FR, but a consistent amount of districts get access to the "best" meme Random: the fluctuations of the number of districts getting access to the "best" meme and other memes	Not available	Not available
Hypothesis of the overall system (GWL) behavior under the PopG and WPG	PopG: increasing overall demand for GW	Not available	Not available

perspective: inverse relationship between GWL and PopG / WPG	WPG: increasing amount of direct GW access points		
Hypothesis of the internal system (ration ratio) behavior: ration ratios decrease overtime for all experiments	Lower ranked DLA agents were designed to continuously learn and apply ration ratios from the “best” performing district	Not available	Not available
Hypothesis of the internal system (WSLs) behavior: The cumulative travelled distance of WUs would increase as ration ratios decrease	WUs would need to travel to multiple WPs to gather the desired amount of water	Not available	Not available
Hypothesis of the internal system (WSLs) behavior: WUs would collect more water from the unsafe sources as ration ratios decrease.	Increased probability of visiting an unsafe type WP in the water collection process due to the requirement of visiting multiple WPs to meet the desired amount of water	Not available	Not available

Table 4: Experimental design summary

The experiment was performed using the implemented model under the behaviour space function with the Netlogo software environment. In the next chapter, the outputs of the experiment are presented and Table 4 will be used to verify the hypothesis, to answer the experimental questions, and to verify whether the experiment was carried out under the designed experimental specifications.

7. Results

The designed experiment described in chapter 6 was implemented and the results are described in this section. The data generated from the simulations were compiled and organized using an open-sourced data analysis software named Rstudio before observing and interpreting the results of the experiment. The results were organized and displayed using multiple graphing techniques and the emerged patterns were identified by the author. The identified patterns were considered observations of the experiment and were analyzed in terms of the overall system behaviour and the internal system behaviour. Interpretations were made for each observation in order to explain what happened in the model to cause the identified patterns to emerge from the simulations.

7.1 Analysis of the overall system behaviour (GWLs) under PopG and WPG

As mentioned in chapter 6, GWLs was selected as the metric to observe in order to identify the overall system behaviour from the ABM experiment. The GWL from each district in every run of the experiment was plotted over time as shown in Figure 13.

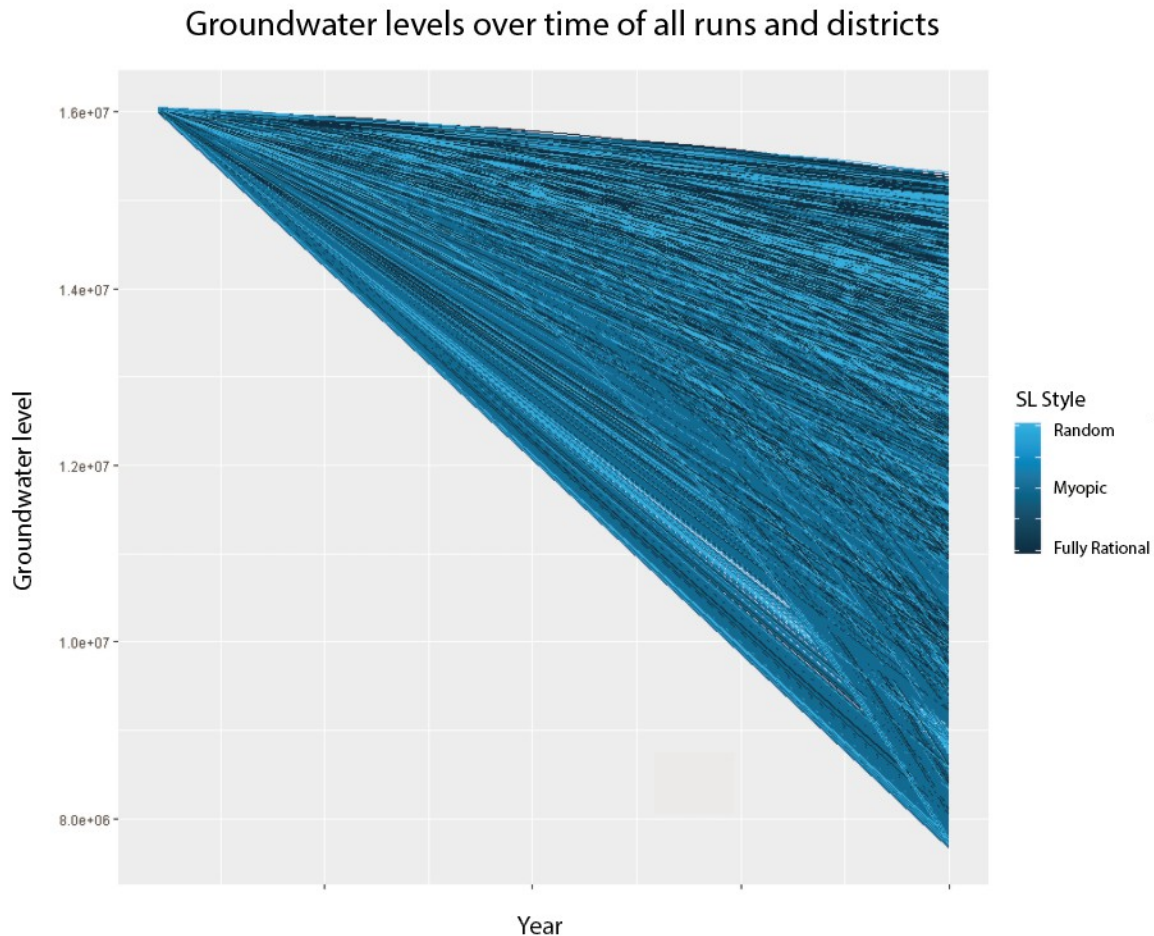


Figure 13: GWLs overtime of all runs and districts

Decreasing GWLs overtime was a pattern emerged from the experiment and observed when GWLs from all runs and districts were plotted over the course of the designed simulation time, as illustrated in Figure 13. The emerged pattern was expected due to assumption 1 and the demand for GW was growing due to the setup of the experiment where population . The overlapping of data points and lines in Figure 13 prevented further investigations on the results of the experiment; therefore additional plots were needed in order to gather further insights. The data from the experiment was separated into the three SL types and visualized using facet box plots as shown in Figure 14(1, 2, 3). A box plot is a way of displaying the distribution of the data by indicating the outlier(s), median, upper and lower quartiles and the variability outside the upper and lower quartiles from a particular group of data.

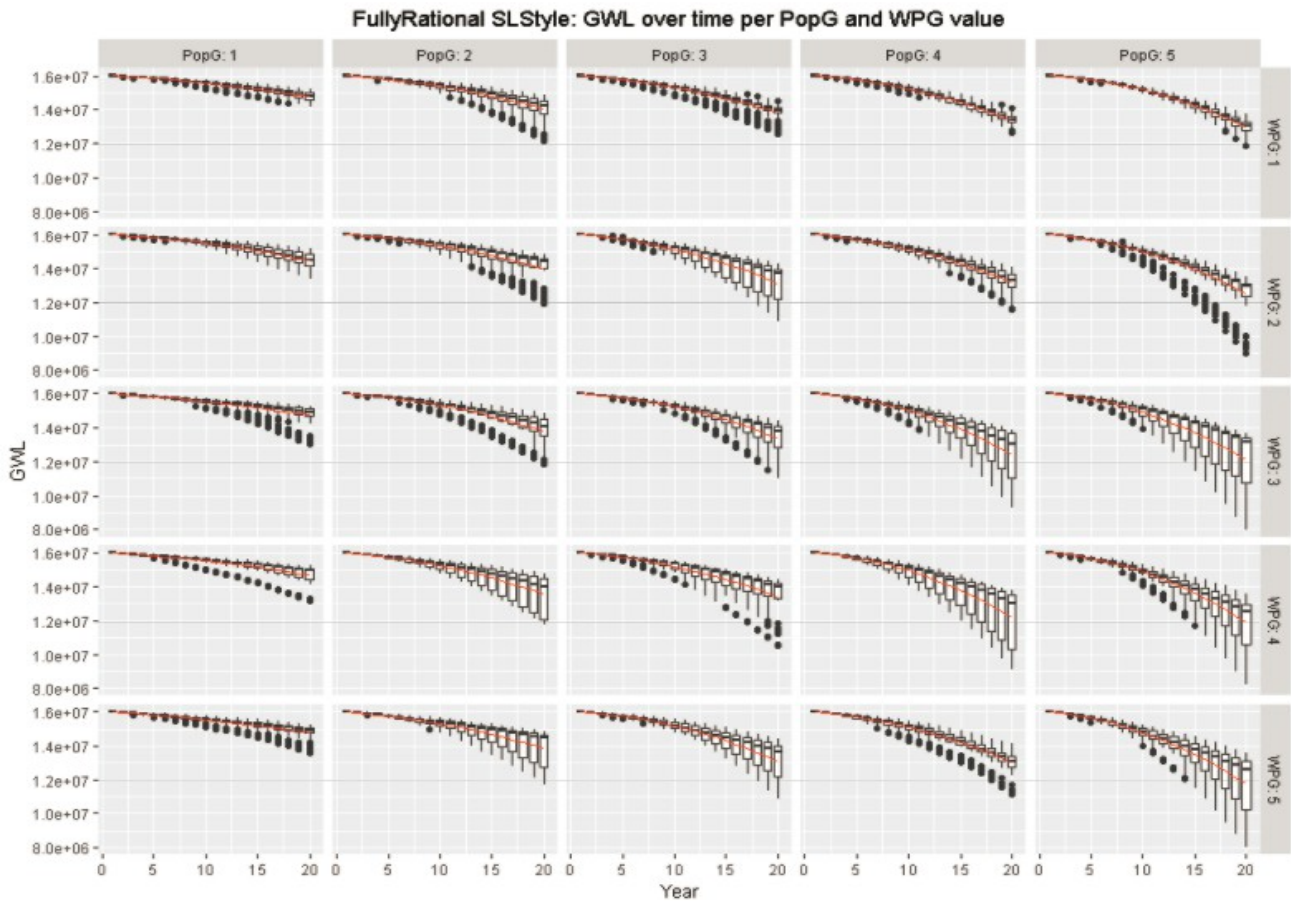


Figure 14 (1): GWLs plotted over simulation time per population growth rate and WP growth rate under FR SL style

The median is represented by the line located in the middle of the box. The upper and lower quartiles are represented by the upper and lower half of the box separated by the median line. The lines extending from the ends of the box are known as “whiskers”; and are used to indicate the upper and lower variability outside the upper and lower quartiles. The outlier(s) are represented by the individual dots which are placed in-line with the “whiskers”.

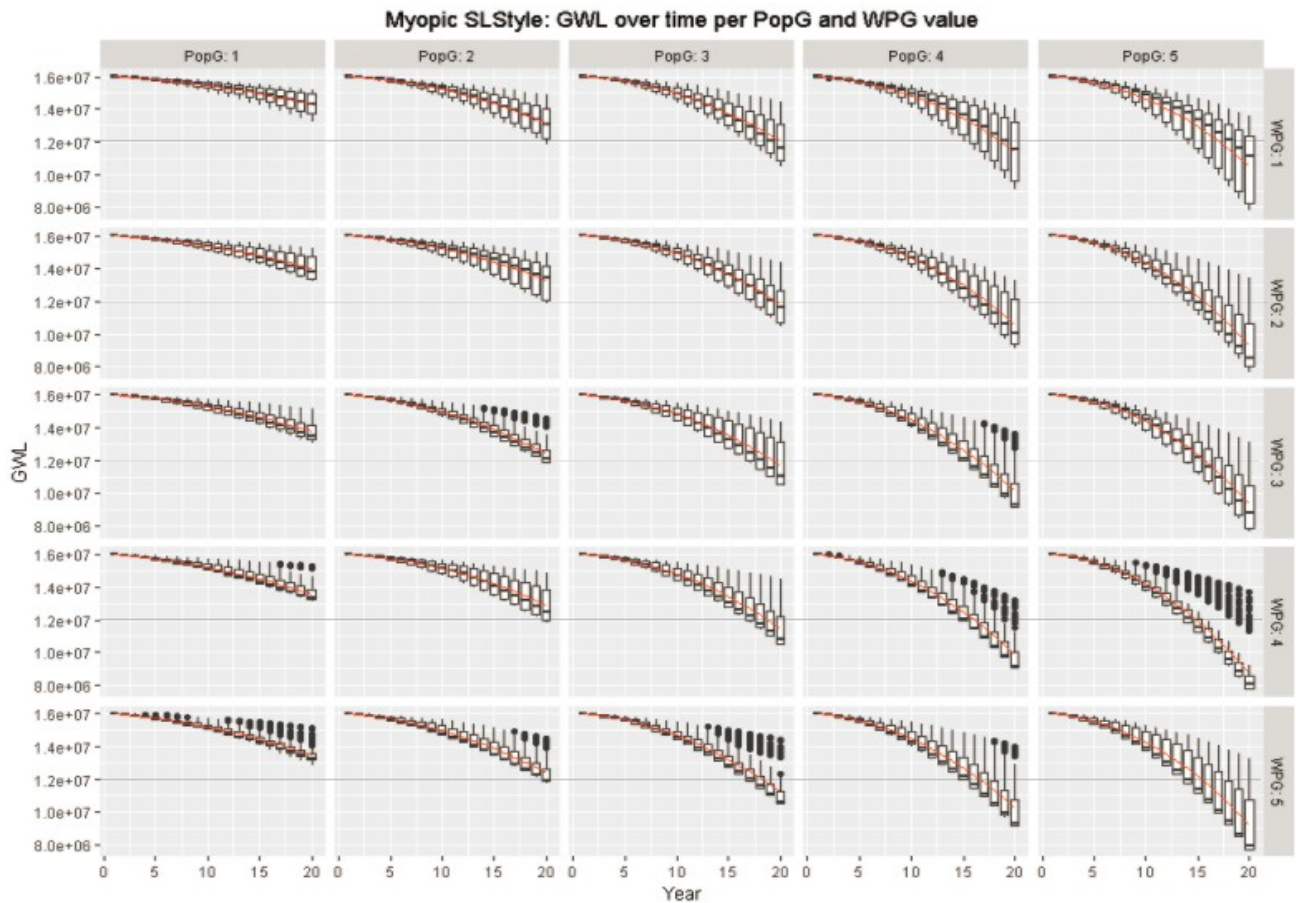


Figure 14 (2): GWLs plotted over simulation time per population growth rate and WP growth rate under myopic SL style

In Figure 14(1, 2, 3), the GWLs from each district were grouped into their respective discrete time and plotted over 20 ticks and the average is indicated by the red line. The box plots were further separated and grouped using faceting in order to display the data in the designed combinations of the experiment mentioned in Figure 12.

From Figure 14(1, 2, 3), a general pattern was emerged from the experiment and was identified; where GWL depletion rates increased as PopG and WPG increased independently or concurrently for all three types of SL. Although the plots mentioned above seemed similar to each other, the observation made above was verified by inspection through the averages displayed in each facet grid plot and by computing a T-test. A T-test is normally used to compare the mean of two data sets under the assumption of a normal distribution with equal variances for both of the data sets (Spector, 2014). The results of a T-test indicates whether the mean of the two data sets used for comparison are equal through the P-value (Spector, 2014). If the p-value is greater than 0.05, it is an indication where the mean values are equal. On the contrary, if the p-value is less than 0.05, it is an indication where the mean values are different.

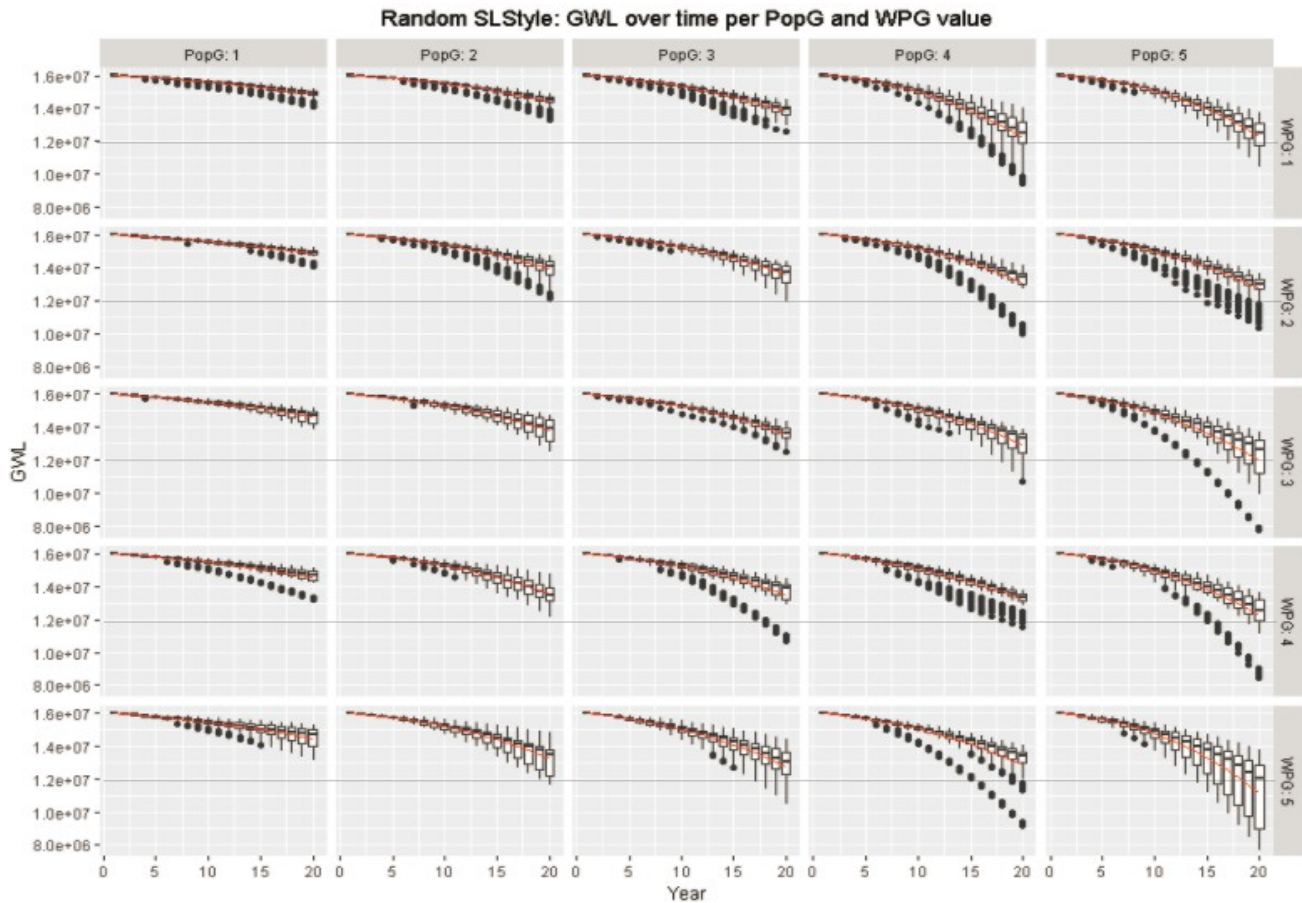


Figure 14 (3): GWLs plotted over simulation time per population growth rate and WP growth rate under random SL style

Since T-tests assumes a normal distribution with equal variances between two data sets, the data from the experiment was transformed before computing the T-tests. A transformation was needed because the untransformed data was left-skewed instead of normally distributed. An example of the untransformed data is shown in Figure 36. According to Kirchner (2001), the left-skewed data can be transformed towards a normal distribution using the ladder of powers. Log transformation is another common technique to transform skewed data as well; however, this technique is more suitable for right-skewed data and including zero values (Kirchner, 2001). Through trial and error, transformation using the power of above 11 yield a data distribution closer to a normalized distribution as shown using an example in Figure 15 and Figure 16; however, the resulting values exceeded the computational limits of the T-test and therefore a cubed transformation was selected to transform the data closer to a normal distribution as shown using an example in Figure 17.

In order to verify the observation made above, a total of sixteen T-tests were computed using the transformed data sets and the results are shown in Appendix L. The setup of the T-tests combinations were according to the four corners of the facet grid presented in Figure 14(1, 2, 3). The data sets from the four corners of the facet grids between FR and random type SL style were compared as well because the averages were similar by inspection and was difficult to determine whether there was a difference between the visualizations.

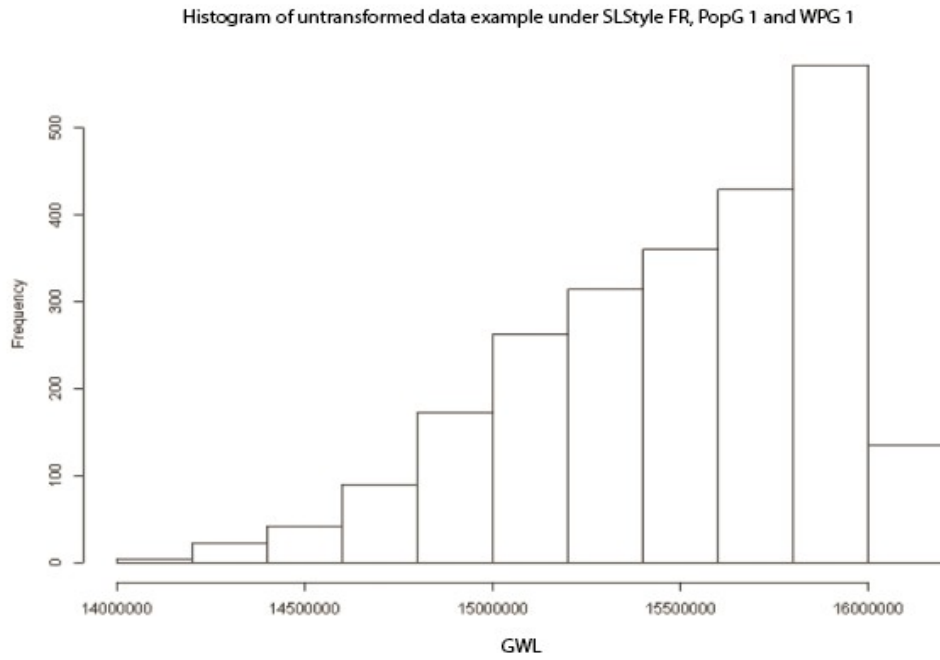


Figure 15: Example of untransformed data distribution visualized using a histogram

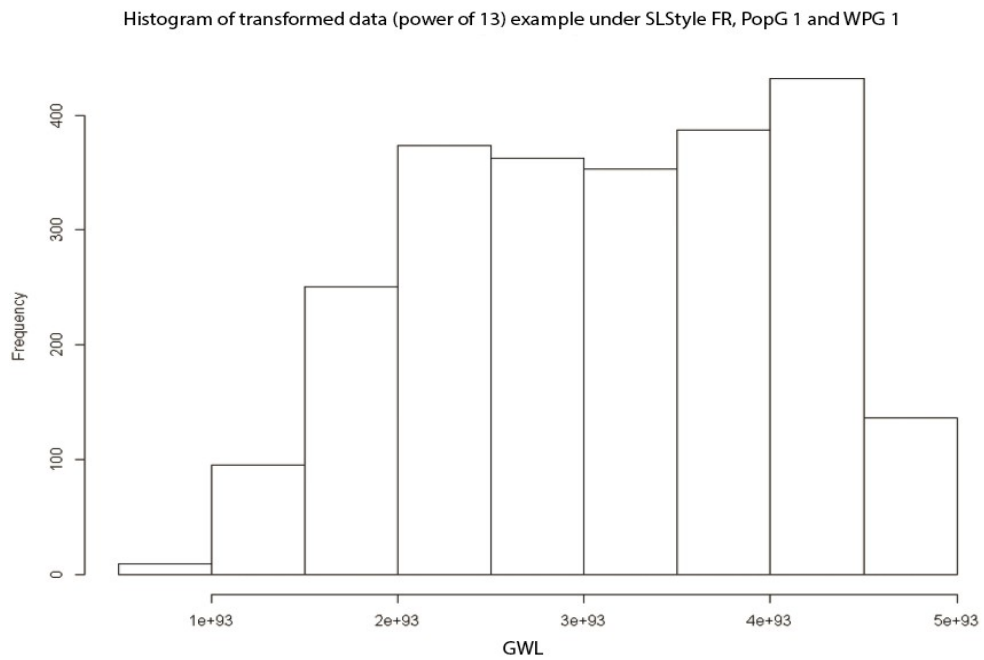


Figure 16: Example of transformed data distribution using the power of thirteen and visualized using a histogram (below)

Histogram of transformed data (power of 3) example under SLStyle FR, PopG 1 and WPG 1

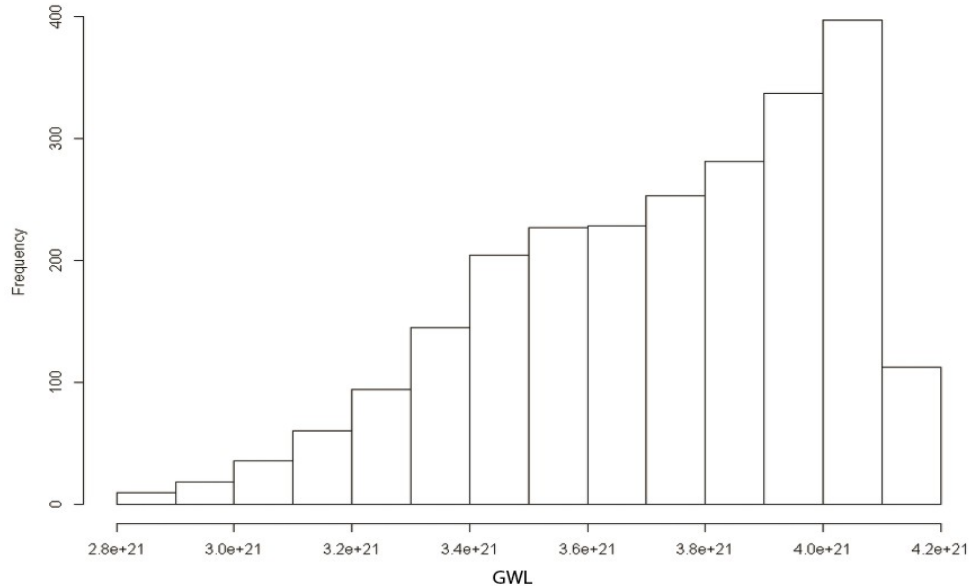


Figure 17: Example of transformed data distribution using the power of three and visualized using a histogram

The overall results of the T-tests indicated as PopG and WPG increased, GWL depletion rates increased as well because of the mean values and P-values of the T-tests. An exception occurred under FR when the lowest PopG and WPG was compared to the lowest PopG and highest WPG setting. The P-values indicated the means between the two data groups were the same and therefore the GWL depletion rates were likely to be the same. Since the majority of the T-tests indicated a change in the mean values, the observation of *GWL depletion rates increased as PopG and WPG increased independently or concurrently for all three types of SL was made.*

The increase of PopG intensified GW depletion rates because the demand of water increases as there were more WU agents in each district. The increase of WPG intensified GW depletion rates as well due to assumption 16 and 18 of the model design. The probability of a new WP agent placed within a return distance of 1.5km to WU agents increases as the amount of WP placed in each district increases; and therefore adjusting the amount of desired amount of litres to be collected at the improved type WP, and allowing a higher amount to be extracted at WP due to the LitresExpected amount calculation. The increasing amount of WP agents in a district also increased the amount of GW extracted if the WP agent is located further than 0.75km of WU agents; because the WP agent would be set to having an expected extraction amount of one WU agent according to assumption 18. This assumption allowed WU agents which were travelling further to collect more improved source of water while other improved type WP alternatives were unavailable. Compared to unsafe type WP agents, there were more GW made available to be directly extracted without the random contribution percentage due to assumption 14; hence increasing GW depletion rates as there were more improved type WP agents in each district.

7.2 Analysis of the overall system behaviour (GWLs) under SL types

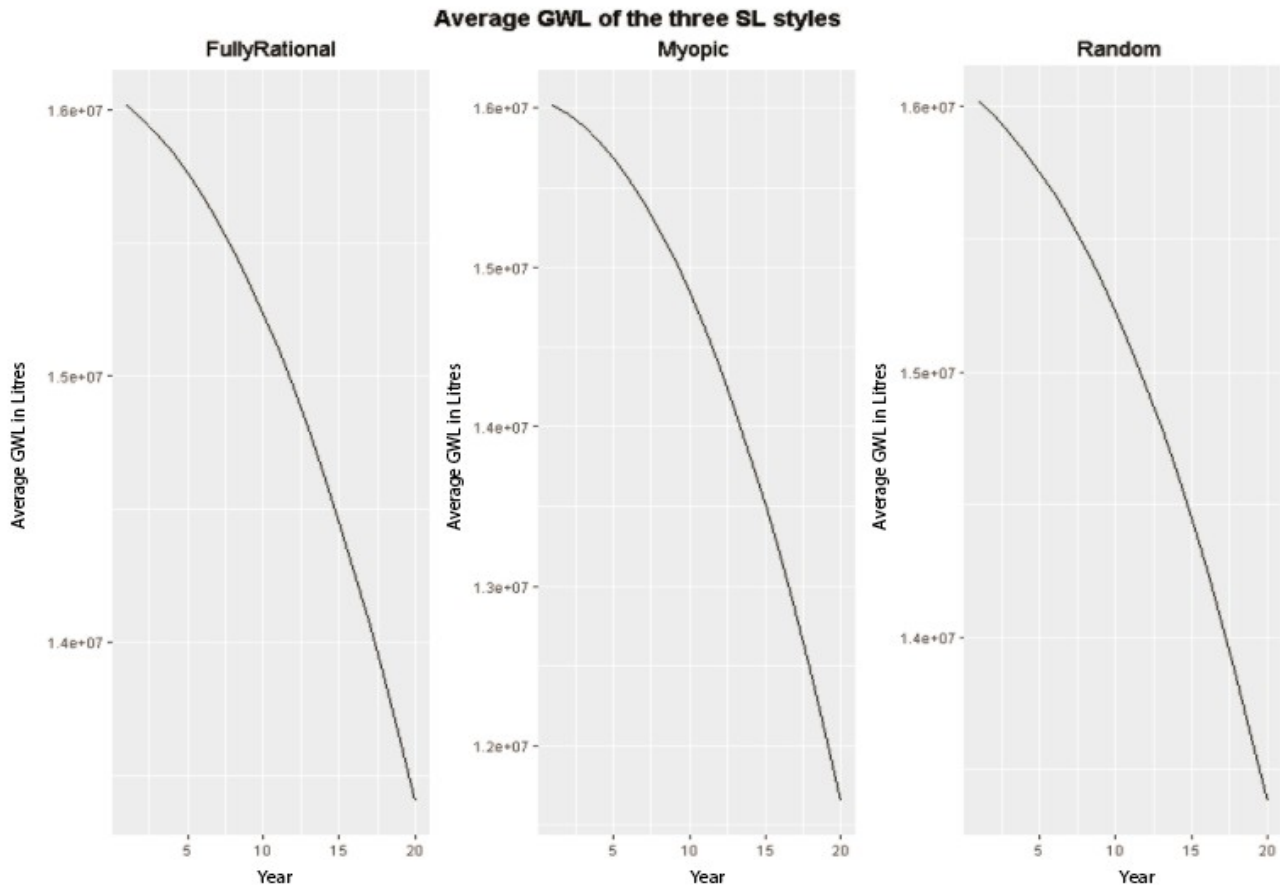


Figure 18: Average GWLs of the three SL styles over simulation time

Besides observing GWL patterns from a PopG and WPG perspective, GWL was observed under the perspective of SL style as well because it was another parameter chosen for a full parameter sweep in the design of the experiment. GWLs were grouped and the averages were plotted according to the respective SL style as shown in Figure 18. An observation was made and an emerged pattern was identified where *FR and random type SL styles performed similarly and better than myopic* in terms of GWLs. This observation was made because FR and random type SL styles displayed an average slightly below $1.3e+7$; while an average of below $1.2e+7$ was shown for myopic SL style. *GWL decreasing overtime* was observed in Figure 13, and was confirmed because the same behaviour was identified in Figure 18.

The performance of random SL style was in between myopic and FR, because districts only occasionally get access to the “best” meme and learning occasions allowed districts to learn from the 2nd best or other ranked districts. The “best” meme here refers to the meme which could lead to the best GWL performance without considering the performance of WSL and other factors besides the performance of GWL. FR had the best overall system performance out of the three SL style because every DLA agents in the system were always in contact with and learning the “best” meme; and therefore, the decision-making and ratio applying phase

included the “best” for most districts under FR. Although random SL style contained the possibility of a higher the amount of districts applying a better ratio than FR, the overall performance of FR was better than random SL style because of the quality of meme the districts were applying. In other words, the possibility of the districts learning, selecting and applying the second “best” or other memes set the performances apart between random and FR SL styles. Myopic had the worst overall system performance despite containing the same amount of districts influenced because DLA agents did not have access to the “best” when the “best” meme were not present in the same region of which DLA agents were designed to learn from in the design of the model.

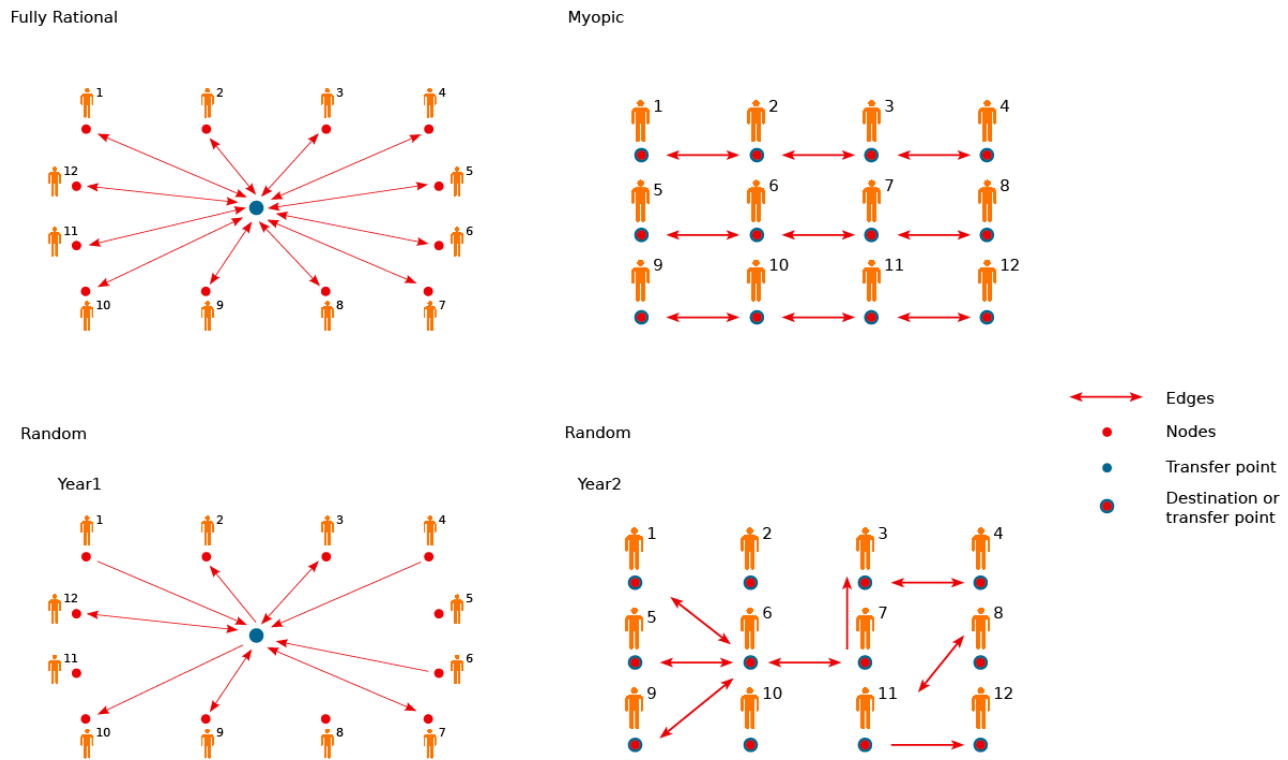


Figure 19: Social learning interpreted using network connectedness theory, transfer points were not included in the designed model and used for the illustration of how agents were connected to each other and can choose to bypass connection with unwanted agents

Although the randomness of the ration ratios given to DLA agents at the beginning of the simulation could have caused the identified pattern to emerge; under the assumption where the repetitions of the experiment were able to remove the uncertainty from the randomness of the given ration ratio, the general properties of the network connectedness theory in CAS can be used to suggest a different interpretation of the results mentioned above. The network connectedness theory allows CAS to be seen as complex networks of physical or abstract interactions (Warnier, 2016). Under the network connectedness theory, elements within CAS are interpreted as nodes and edges only and CAS can be more or less robust or resilient based on the connectedness of the network. Figure 19 is an illustration of the network structures of the designed CAS used in the experiment from each SL style. The nodes represents DLA agents in the model, while edges represents a connection which allows DLA to share and learn memes. A bi-directional edge indicates DLA agents were able to share and

learn from each other and a single directional edge indicates the particular DLA agent can only learn from the DLA agent the edge is pointing towards. The transparent edges indicate the connection was present although the DLA agent did not choose to share or learn from the other DLA agent. Filled edges indicate the connection was present and consistent in the network.

The learning network in FR was set up to be highly, fully and steadily connected in this study, this is indicated by the amount of bi-directional edges in Figure 19. Under the network structure in FR, every district could get access to the “best” meme to apply at WPs to control GWLs. As a result, the overall system behaviour (GWL) were more desired most of the time. This also reflects a more robust overall system at the national level (resisting the total GWL depletion increase rates), while the system is more resilient in the regional or district level (trying to get as close to the GWL the particular district had in the previous year). The highly steady and connected network eliminates the probability of learning from a lower performing district, resulting in a higher overall system behaviour

The learning network under myopic was set up to be highly steady and less connected as DLA agents were fully connected only within their own respective regions in the model as shown in Figure 19. Less connected networks in the model lead to certain amounts of districts not able to get access to the “best” meme to apply at WPs; and therefore resulting the lowest overall GWL performance because the network eliminates the probability of learning from the best performing district for the whole system.

Random SL style was designed to contain a highly connected and less steady network compared to the other two forms of SL style as shown in Figure 19. This formation of the network reduces the probability of learning from the best performing for the whole system, and increase the probability of learning from better performing districts while not being confined to memes within their region.

The other two forms of SL were not designed to allow learning from better performing and only learning from the best performing district within the network. As a result, there were an increased amount of districts performing closer to the best performing district in the system and leading to a better overall performance than myopic SL style. The overall performances under random SL style were worse than FR nonetheless because DLA agents were able to learn and apply memes from better performing districts instead of always learning and applying from the best district under FR. The fact where the network was less steady under random SL style can also be interpreted as less connected than FR, where DLA agents could only occasionally get access to the best meme leading to performances lower than districts under FR. According to the insights gained from the application of network connectedness theory, network steadiness and connectedness contributes to the overall system performance; where steadier and highly connected networks could yield a more desired overall system behaviour (GWL). Connectedness was identified to have a higher importance over steadiness because of the difference in performance between random and myopic SL style shown in Figure 18.

7.3 Analysis of the general internal system behaviour (ration ratios) under SL types

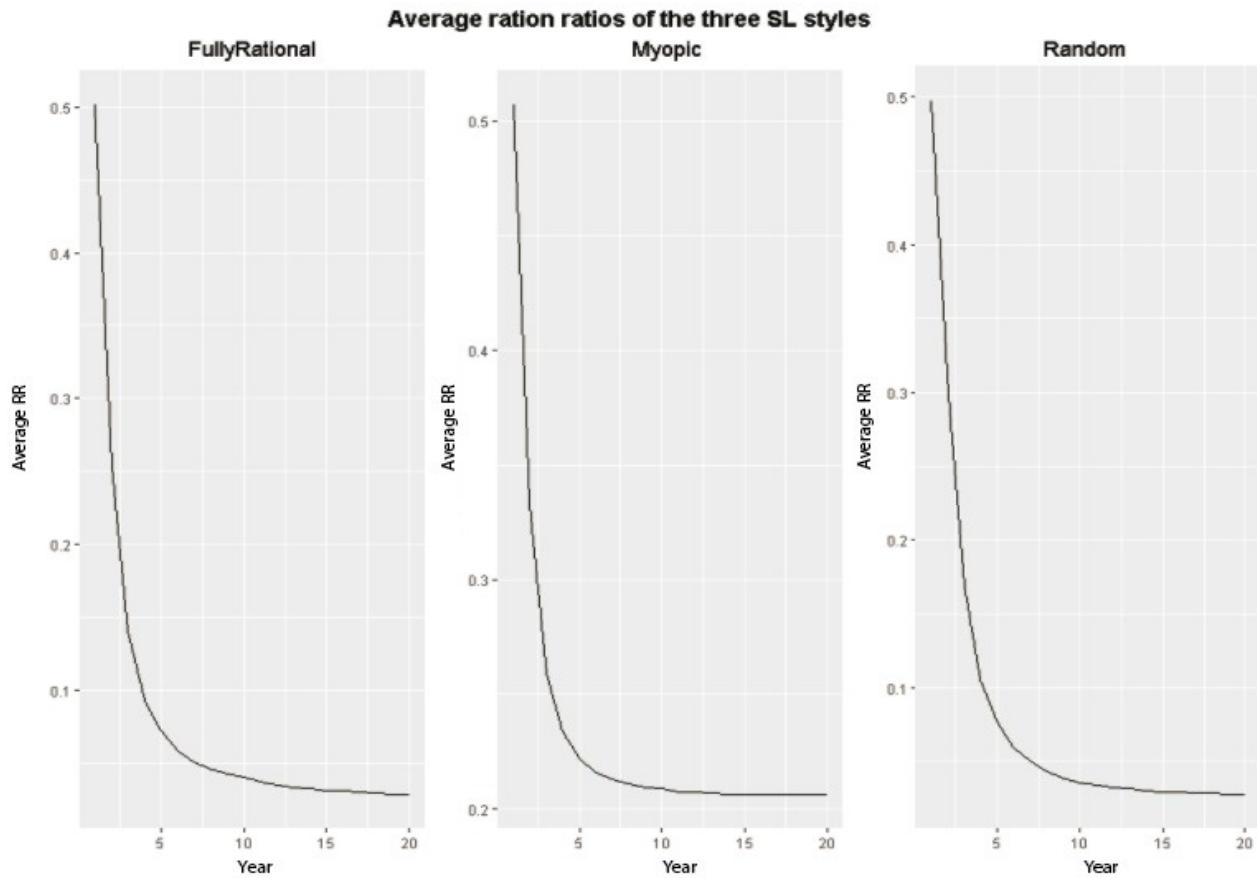


Figure 20: Average ration ratios of the three SL styles over simulation time

Since ration ratios were designed to influence GWLs and therefore should be observed for further gaining of insights. The ration ratios were grouped and plotted using facet box plots again and shown in Figure 20. The ration ratio averages from all experimental combinations began near 0.50 and were lowered after 20 ticks from the facet plots. The average ration ratios under FR and random SL style experiments approached 0.00 towards the end of the simulation. On the other hand, the average ration ratios under myopic experiments approached 0.25 towards the end of the simulation. However, the facet plots made it difficult to confirm the observed pattern and the average ration ratios based on the three SL types were plotted. As shown in Figure 20, the average ration ratios from all three SL styles matches with the observed pattern from the ration ratio facet plots. Therefore, *ration ratio approaching zero over time* was another observed emerged pattern from the results of the simulation.

Based on the average GWL and ration ratio performances shown in Figure 18 and 20, a correlation could be made. *As ration ratio decreases, GWL depletion rate decreases leading to a better overall system performance of a higher GWL.* This was identified by the distinct GWL and ration ratio from myopic when compared to the other two SL styles; where the average GWL were lower and ration ratio were higher when compared to the other two SL styles. Similar to myopic, random SL style had a higher ration ratio average than FR and a

lower average GWL when compared to FR.

Ration ratios approached zero over time in the experiment because DLA agents only considered the performance of GWL when learning and applying ration ratios without consideration of WSL or other factors. The correlation between average GWL and ration ratio mentioned above could help explain why ration ratios approach zero over time under the designed decision making consideration format. The districts of which contained a ration ratio closer to zero performed better than other districts because WUs had less direct access to GW resources; and therefore, WUs collected less water due to the increased travelling distance from restricted water points. In addition to the access and travelled distance, the way the model was designed to allocate unsafe sources also contributes to interpretation of why ration ratios approached zero over time. As ration ratios decreased, the amount of water made available to be accessed by WUs at the improved type WP decreased. WU agents were required to travel further to other WPs to collect water by the design of the model. If WU agents were visiting an unsafe WP, only a random portion of the water collected from unsafe sources was allocated towards GW resources. Unsafe water allocation, restricted access due to a lower ration ratio and distance limitations lead to a better GWL performance for the particular distance because less GW was being withdrawn by WUs. A better GWL performance lead to a higher probability of other DLA agents learning and applying the meme from the better GWL performing district in the selection phase of the model; because the list of memes the DLA agent contained was sorted by the performance of GWL and learns from the top (half) of the list.

Network theory can be applied again to suggest an explanation on the average ration ratio behaviour displayed in Figure 19. As the network was highly connected and steady in FR, there were more districts learning from the best district in the system, of which was likely to contain a ration ratio closer to zero. DLA agents were separated in to regions under myopic SL style in a less connected and highly steady network, the best performing district in each region could contain a ration ratio further away from zero for other DLA agents to learning, leading to a higher average of ration ratio. Less steady and highly connected networks such as random SL style delays when DLA agents get access to the “best” meme and DLA could sometimes learn and apply ration ratios from DLA agents with lower GWL performance when compared to the best district; which was likely to contain a ration ratio slightly further away from zero and to have caused. The combination of the unsafe water allocation, travelled distance, access to GW resources and network theory have lead to the interpretation of why ration ratios approached zero over time.

7.4 Analysis of the overall and internal system behaviour (GWL and ration ratios) at the estimated point of reality

The average ration ratios and GWLs shown in Figure 18 and 20 were derived from every PopG and WPG combination, a particular PopG and WPG setting of the experiment was chosen to represent the estimated point of reality in Uganda. According to the 2014 census in Uganda, population was estimated to grow at 3% annually; while the data from the national water reports also reported an average annual increase of 3% in the past 10 years. Since the amount of functional WP was significantly less than the population of Uganda, the data under the lowest WPG and the highest PopG were argued to represent reality.

Although GW rationing and SL for GW resource management was not applied in Uganda at the time of the study, random SL style was estimated to be closest to reality if GW rationing was to be performed under SL from this experiment. This was because DLA agents under random SL type were designed to decide whether or not to learn and apply ration ratio in the model. In reality, actors might not be applying or learning all the information about ration ratio if one decides to prioritize WSL or other factors over GWL at different moments or decides if the received information was not useful to individuals. Information is not always available or at least delayed in Uganda (Knipschild, 2016), which is represented by the inconsistency of DLA agents learning from the same agents in their region or across the nation.

There are multiple learning associations and organizations in Uganda's WASH sector to spread information; however, actors do not always learn and apply what they have learned as mentioned above. Therefore, random SL type represents reality the closest if GW rationing was to be performed under SL. Myopic can be the future evolved forms of "reality", when institutions and organizations demand rational ratios to be learned under these SL structures; and FR was unsuitable because humans are bounded rational (Selten, 1999). The average ration ratios and GWLs were plotted once again for the estimated point of reality as shown in Figure 21 and 22. Random type SL style performed second to FR again and ration ratios behaviour were similar to Figure 18; thus confirming the observations made previously.

Average GWLs of the three SL styles under PopG5 WPG1

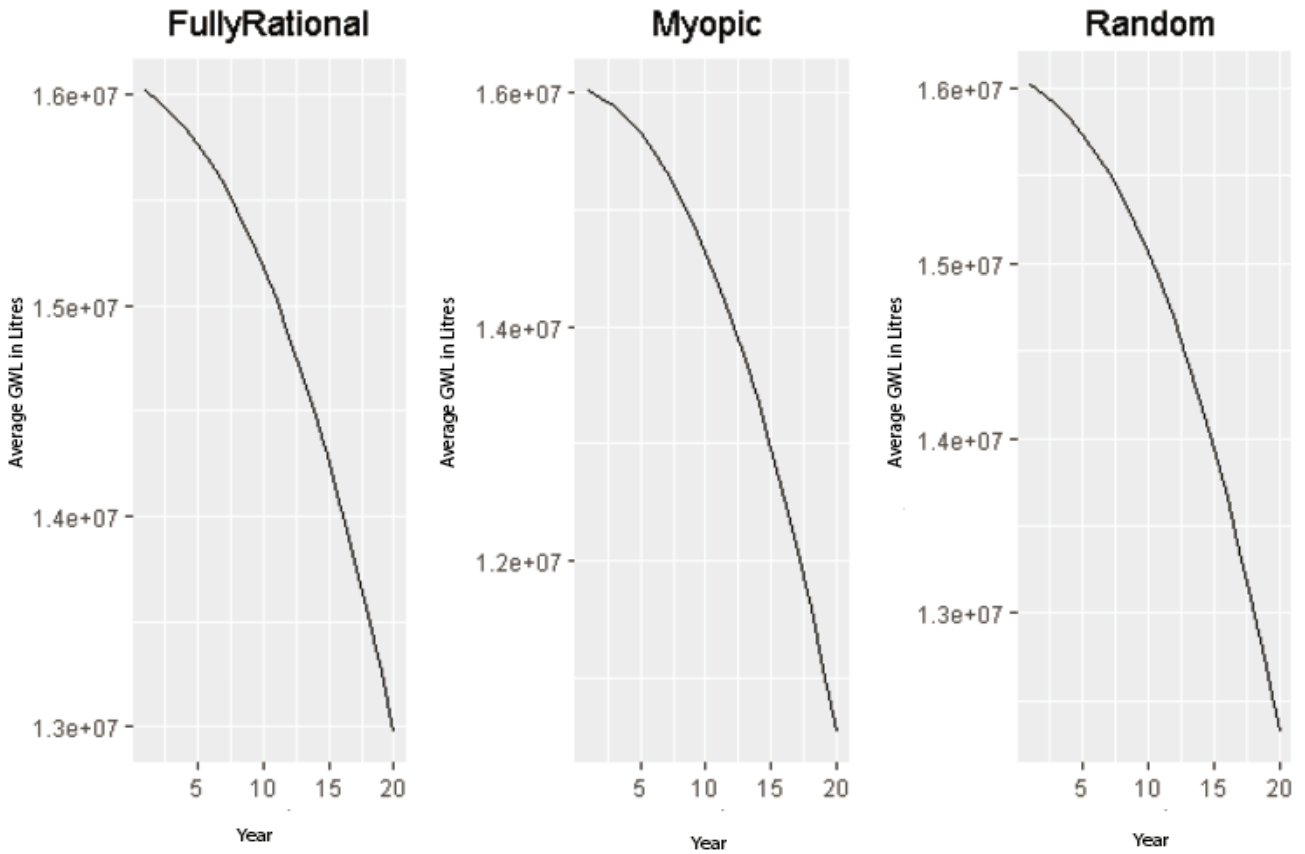


Figure 21: Average GWL of the three SL styles over simulation time at the estimated point of reality

Average ration ratios of the three SL styles under PopG5 WPG1

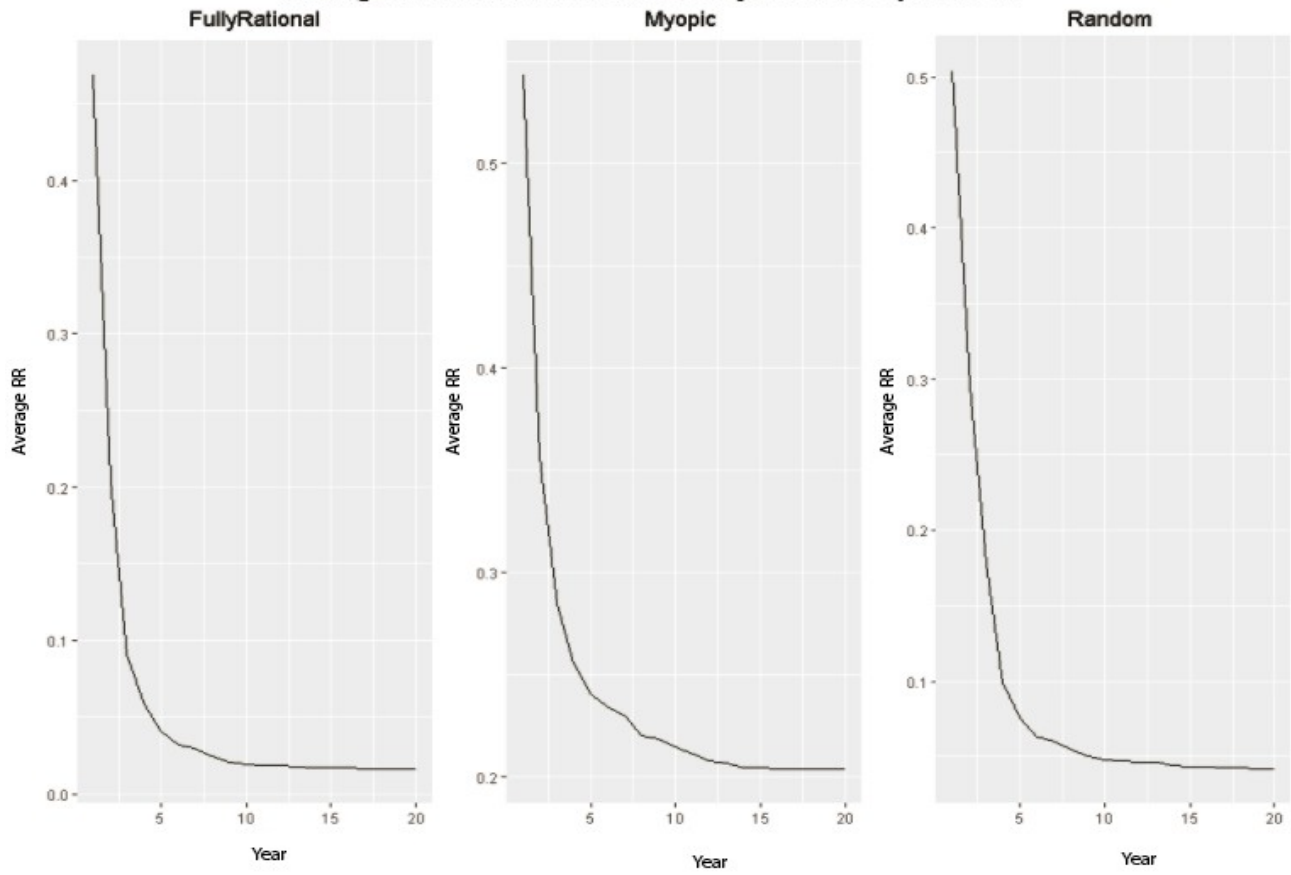


Figure 22: Average ration ratios of the three SL styles over simulation time at the estimated point of reality

7.5 Analysis of the internal system behaviour (WSL and cumulative travelled distance) at the estimated point of reality

Other internal system behaviour characteristics were observed at the estimated point of reality to gain further insights from the experimental results. As mentioned in chapter 6, water collection portfolios and cumulative travelled distance from WU agents were chosen as internal system behaviour metrics to be observed for this experiment. The ration ratios, fractional water collection portfolios and cumulative travelled distance were grouped into categories and plotted in a histogram format. Each histogram were made to display the average ration ratios, cumulative travelled distance and average water collection portfolios at each tick of the simulation from the ten experimental runs. The histograms made from the data generated at the beginning and the end of the simulation is shown in Figure 23a and Figure 23b respectively.

The average ration ratios decreased from around 0.5 towards 0.0 over twenty ticks. There were about an equal amounts of WUs contained a water collection portfolio of less than 10% water from improved type WP and a water collection portfolio of 100% water from improved type WP at the beginning of the simulation. There were also about an equal amount of WU contained a cumulative travelling distance of less than 1.5km and more than 3.0km at the beginning of the simulation. WUs contained a water collection portfolio of 100% water from improved type WP were considered containing the best water collection portfolio, and WUs contained a water collection portfolio of less than 10% water from improved type WP were considered containing the worst water collection portfolio. WUs contained a cumulative travelled distance of less than 1.5km were considered having the best cumulative travelled distance; which WUs containing a cumulative travelled distance of more than 1.5km were considered having the worst cumulative travelled distance.

Towards the end of the simulation, the average water collection portfolios and cumulative travelled distance were no longer equal between the best and worst water collection fraction and cumulative travelled distance. About two-thirds of the WUs contained the worst water collection portfolio and the worst cumulative travelled distance status from the experimental results. An observation was made based the comparison between the two histograms displayed in Figure 23a and Figure 23b; *as ration ratio decreases, the amount of WUs contained the worst cumulative travelled distance and water collection portfolio increases leading to undesired WSL from GW rationing.*

Again, limited WP access from a lowered ration ratio increased the amount of WUs having to travel further to collect the desired amount of water; and therefore collecting lesser volume of water as well. Limited WP access from a lowered ration ratio also increased the amount of WUs having to collect water from unsafe sources within the district the improved type WPs were non-functional due to rationing. The WSL displayed in Figure 23b was considered undesired because the national targeted quantity of water collected from improved sources were 20 litres per day per WU and WUs should experience a cumulative travel distance of less than 1.5km as the criteria of the targeted basic WSL.

Internal system behavior of Random SL type WPG1 PopG5 at year:1

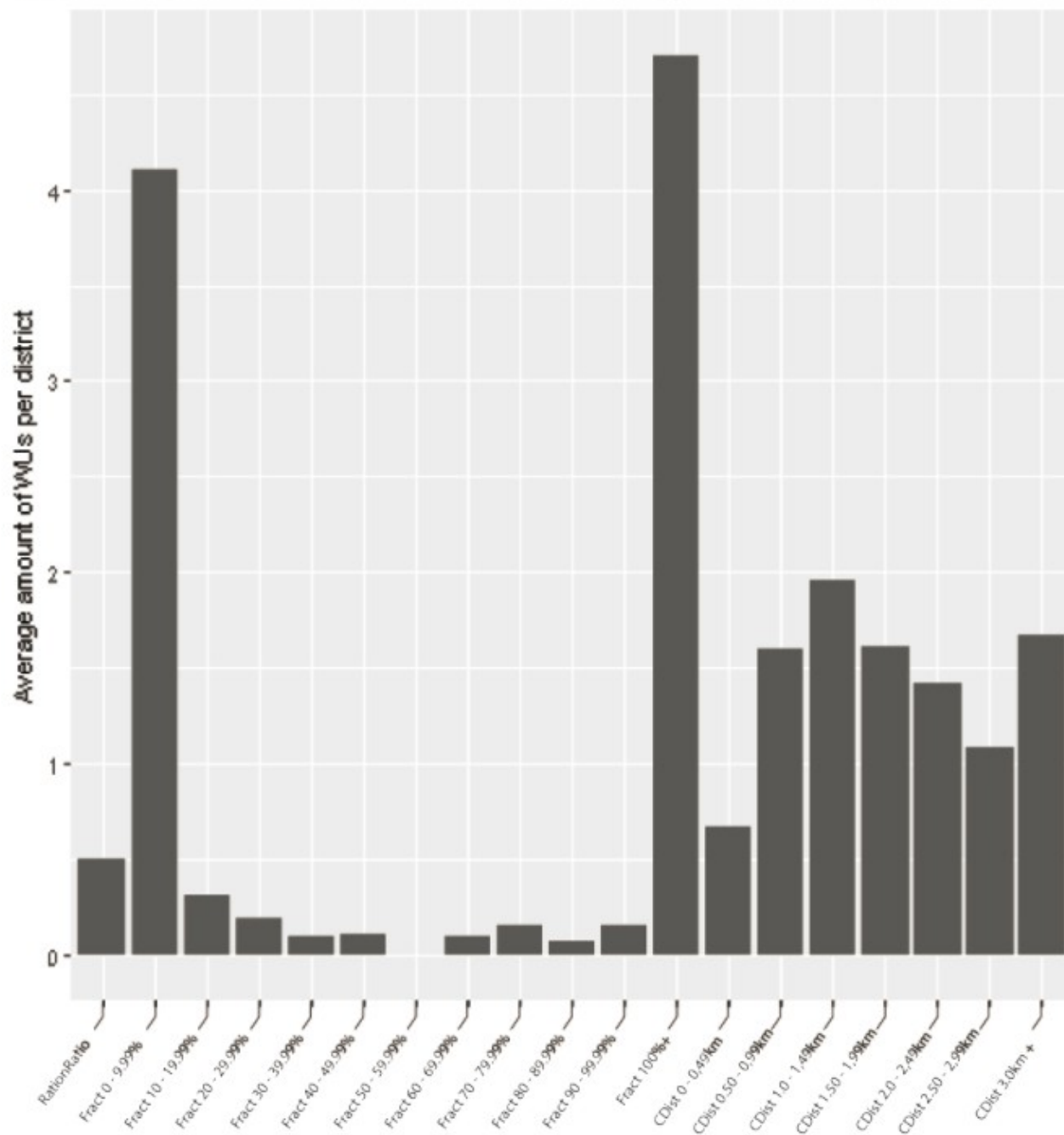


Figure 23a: Histogram of the internal system behaviour at the first tick of the simulation, Fract represents the fraction between the amount of water collected from improved sources and unsafe sources, Cdist represents the cumulative distance travelled.

Internal system behavior of Random SL type WPG1 PopG5 at year:20

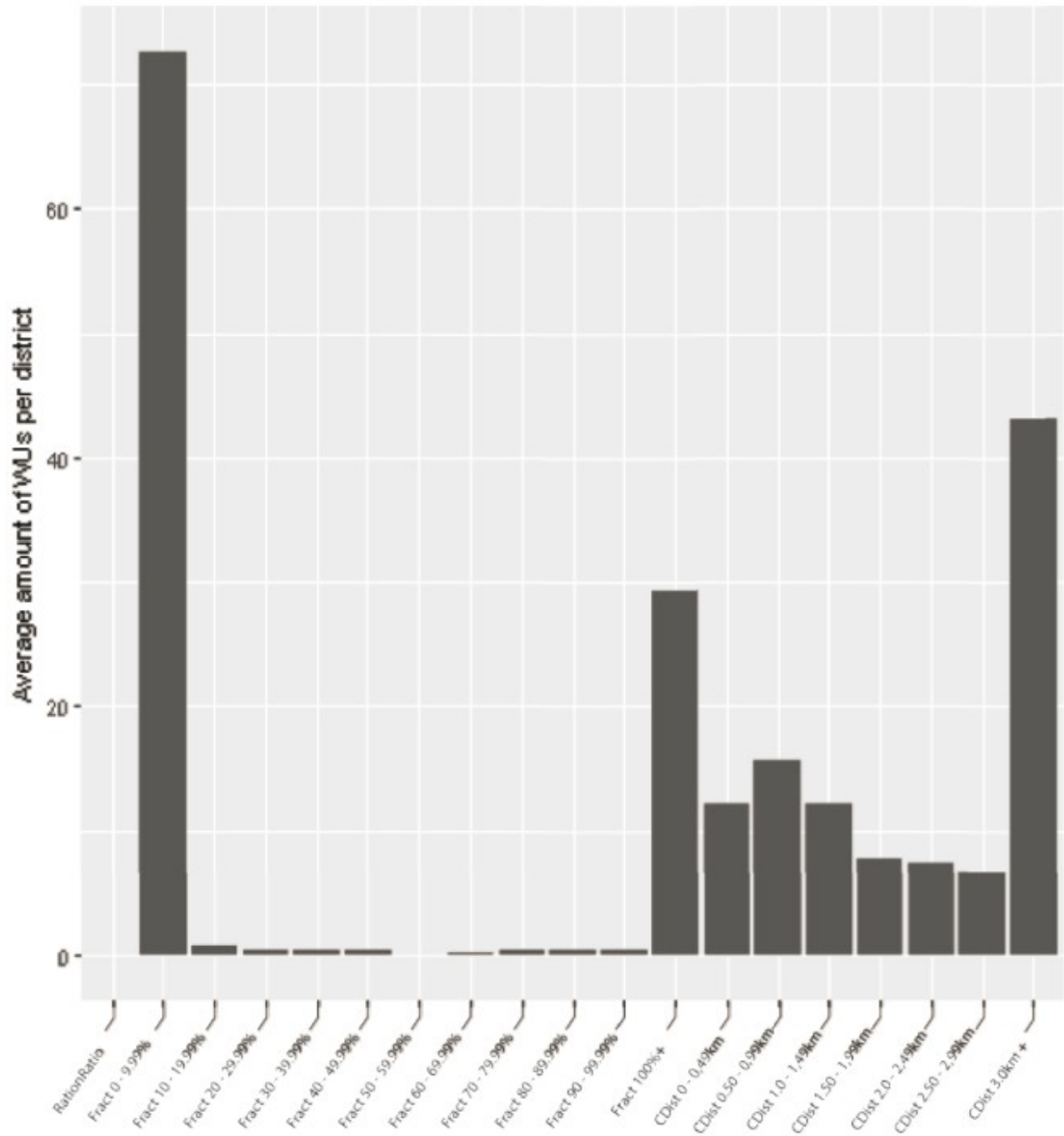


Figure 23b: Histogram of the internal system behaviour at the last tick of the simulation, Fract represents the fraction between the amount of water collected from improved sources and unsafe sources, Cdist represents the cumulative distance travelled.

7.5 Summary of the experiment and results

From this chapter, several observations and interpretations were made based on the results of the experiment on the overall and internal system performance. A table was made to summarize the results and findings of the experiment (Table 5) and to compare with the hypothesis made for this experiment in section 6.3 to conclude the experiment.

Experimental design	Why?	Experimental Results	Why?
Full factorial parameter sweep	See section 6.1	Carried out	See chapter 6
Would a pattern about GWLs and WSL emerge from different SL diffusion for GW rationing? - Hypothesis: Yes	Because of the changing environment in the model	Yes , a pattern emerged under different SL types	GW depletion rates and ration ratios behaviour were different under different SL types (the changing environment)
Hypothesis of the overall system (GWL performance) behavior: FR > Myopic > Random	FR: All districts have access to the “best” meme Myopic: contains the same number of districts affected as FR, but a consistent amount of districts get access to the “best” meme Random: the fluctuations of the number of districts getting access to the “best” meme and other memes	Hypothesis rejected: FR > Random > Myopic	Network theory suggested connectedness and steadiness of the SL networks matter, and connectedness was of a higher importance in the designed model. FR had the highest above mentioned attributes in the experiment. Random type SL contained a higher level of connectedness over myopic and districts were able to learn from a range of other better performing districts. Therefore, the amount of influenced districts were often higher than myopic.
Hypothesis of the overall system (GWL) behavior under the PopG and WPG perspective: inverse relationship between GWL and PopG / WPG	PopG: increasing overall demand for GW WPG: increasing amount of direct GW access points	Hypothesis stands	Hypothesis reasoning holds

Hypothesis of the internal system (ration ratio) behavior: ration ratios decrease overtime for all experiments	Lower ranked DLA agents were designed to continuously learn and apply ration ratios from the “best” performing district	Hypothesis stands	Hypothesis reasoning holds. The network theory can be used to suggest the changing magnitude of ration ratio decrease; where highly connected and steady networks can increase the average decrease rate of ration ratios as there was a higher amount of districts getting access to and to learn from the “better” performing district which contained lower ration ratios. Connectedness was again considered of higher importance here.
Hypothesis of the internal system (WSLs) behavior: The cumulative travelled distance of WUs would increase as ration ratios decrease	WUs would need to travel to multiple WPs to gather the desired amount of water	Hypothesis stands at the estimated point of reality	Hypothesis reasoning holds
Hypothesis of the internal system (WSLs) behavior: WUs would collect more water from the unsafe sources as ration ratios decrease.	Increased probability of visiting an unsafe type WP in the water collection process due to the requirement of visiting multiple WPs to meet the desired amount of water	Hypothesis stands at the estimated point of reality	Hypothesis reasoning holds

Table 5: Experimental design summary

According to table 5, a majority of the hypothesis made for the experiment were correct with the exception of the overall GWL performance under different SL types. Under the overall system perspective, the hypothesis made about GWL decreasing overtime and the rate of depletion increases as PopG and WPG independently or concurrently was correct within the scope of this study. As PopG increases, the overall demand for GW increases leading to the increase of GWL depletion rates. As WPG increases, the amount of direct GW access points for WUs to gather water increases leading to the increase of GWL depletion rates.

However, the hypothesis made about the GWL behaviour under different SL types was rejected within the scope of this study. FR showed the highest GWL performance, followed by

random then myopic. Random and FR SL style showed similar GWL performances in general; while myopic SL style was outperformed in comparison to the other two SL styles. The network theory suggested the level of connectedness and steadiness in SL networks matter, and connectedness was of a higher importance in the designed model. FR had the highest above mentioned network attributes in the experiment; therefore, FR type experiments outperformed the other SL types in general. Random type SL contained a higher level of connectedness over myopic in general and districts were able to learn from a range of other better performing districts; therefore, the amount of influenced districts were often higher than myopic despite the fluctuations on the amount of influenced districts. Since ration ratios were designed to influence GWLs in the designed model, myopic type experiments resonated with the GWL performance results of the same type; where the average ration ratios after 20 ticks were higher than the other two SL types. FR and random SL type experiments showed similar average ration ratio results after 20 ticks as well; and the use of the network theory described above to interpret the above mentioned average ration ratio behaviour was suggested.

The internal system behaviour at the point of estimated reality showed ration ratios were changing towards zero over the course of the simulation, and as ration ratio decreases, the amount of WUs contained the worst cumulative travelled distance and water collection portfolio increases leading to undesired WSL from GW rationing. As a result, the hypothesis of increasing cumulative travelled distance and the volume of water collected from an unsafe source as ration ratios are decreasing was observed in the experimental outcomes. WUs were forced to travel further distances to collect enough water under the increasing rationing restrictions in the model; leading to the interpretation of the above mentioned internal system behaviour to emerge in the simulations. Lastly, the probability of visiting an unsafe type WP in the water collection process increased as ration ratio decreased; leading to the observation of the increasing average amount of water collection portfolios in the experimental results was suggested. Due to the requirement of visiting multiple WPs to meet the desired amount of water as ration ratios decreased in the design of the model, the interpretation of the above mentioned probability increase was suggested.

From this chapter, the experimental results were shown and discussed with regards to what happened in the simulations; and the suggested interpretations on the observations made about the emerged patterns of the experiment. In this section, an overview of the experimental results was made and compared with the hypothesis of the designed experiment. In the next section, the discussion continues on the limitations of the research process and how well did the observations and interpretations made in this chapter relate to the reality in Uganda's RWSD.

8. Discussion

In this chapter, the design of the model, observations, interpretations and the research process presented in the previous chapters will be discussed. In section 8.1, the discussion begins with the validity of the designed model, observations and interpretations; and in section 8.2, the limitations of the research process is discussed.

8.1 Validation discussion

Due to the resources available and time constraint of the project, expert interview was the selected method for the validation phase of the project. The validation phase was implemented because it is the ninth step in the ABM practice guideline presented in chapter 5 and to verify if the insights gained in the previous chapter and the designed model reflect reality. The designed model, experimental results, observations and interpretations were presented to domain experts to gain feedback for the validation phase of the project. The domain experts interviewed and consulted is shown in Table 6.

Domain expert	Expertise
Angela Huston	Programme Officer, IRC
Deirdre Casella	PhD candidate with research interests in SL and governance of WASH, Delft University of Technology

Table 6: Domain experts consulted in the validation interview meeting

The domain experts were asked to reflect on the presented findings from the ABM experiment in terms of how did the results of the experiment and the design of the model reflect reality based on the experiences from the domain experts. The full summary of the meeting is documented in Appendix M. The full summary of the insights gained after the interview with regards to the model design is documented in Appendix N; and the full summary of the insights gained after the interview with regards to the findings and interpretations of the experimental results is documented in Appendix O. In section 8.1.1, the validity of the designed model is briefly discussed; and in section 8.1.2, a brief discussion on the validity of the findings and interpretation of the experiment is presented. The domain experts were also asked to provide recommendations based on the findings of the experiment and the design of the model in the same meeting. The recommendations from the domain experts will be discussed in chapter 9.

8.1.1 Validation discussion: designed model

In general, the designed model was sufficient for the purpose of this research according the domain experts. However, there were parts of the model which did not represent the reality in Uganda and the main issues are discussed below. Firstly, the absence of geographical and hydro-geological characteristics does not reflect how WU travel and GWL responds to domestic GW demand in reality. The total travelling distance for WUs might differ as the local conditions are different. The resulting GWLs might also lead to a different pattern along with

the inclusion of GW recharge. Secondly, placing new WP agents randomly in each district at every tick of the simulation and does not reflect how new WPs are placed in reality. The placement of a new improved type WP depends on the local hydro-geological and geographical conditions and could lead to different results in reality. The placement of a new WP also depends on financial allocations from the national conditional grant each district receives annually which the model excluded as it was outside of the scope of this study. Thirdly, the random placement of WU in each district at every tick does not reflect the current and future micro and macro migration and settlement patterns of WUs in reality. Although the inclusion of an accurate settlement pattern falls outside of the scope of this study, it is important to recognize the results could be affected by this aspect because this would affect the travelling distance of a WU agent and how WP agents would behave under the designed rationing sequence. Lastly, the way WU agents was modelled to behave in the simulations only partially reflect the actual WU experience in reality. The assumption of always visiting improved type WPs first followed by the next closest WP regardless of type was suggested as a correct way of modelling WU water collection behaviour. However, the assumed water collection behaviour does not completely reflect WU experience in reality due to the absence of learning for WU agents in the model. A different result could emerge when WUs can learn from the word of mouth or learn from experience. For example, if a WU cannot collect any water from a particular WP consistently, the WU could decide to visit a more reliable WP directly and lead to a different WSL result.

8.1.2 Validation discussion: experimental results and findings

The GWL and rationing results of the experiment suggested a pattern under extreme situations or other forms of rationing in Uganda. This is because under extreme situations, WUs and decision makers are more likely to accept and act towards the extreme rationing RWSD situations. Under non-critical situations, learning and applying ration ratios would not result in the way it was presented (close to 0%) and there should be a greater amount of water available for extraction. This is because different decision makers have different priorities in their own respective agendas. In other words, DLA agents stop learning and applying ration ratios at some point during the simulation according to their own agendas. GW rationing on rural domestic users also only makes sense when they are obtaining more than 20L/d; however, decision makers would not ration below basic WSL unless it is in an extreme situation.

Although the way WU agents were modelled to behave in the simulations did not reflect the actual WU experience in reality, the results also suggested an informal form of rationing where GW rationing is not regulated from governmental authorities. Piped networks represent a scenario where rationing behaviour from the experiment results potentially reflects situations in reality. Consider a piped network with a fixed volume of water supply which completely depleted. The rationing behaviour from the experiment resembled a part of the reality according to the described situation above, where WUs could be forced to only collecting 5L per person, as the supply system is depleted instead of being forced to collect 5L per person due to rationing regulations.

It is important to note however, the insights gained from the expert interview described in section 8.1.1 and section 8.1.2 are indicative and preliminary; because expert interviews are

biased and the number of experts interviewed were insufficient to represent the majority of the experts in the field. Nonetheless, the insights presented in this section is the first attempt to validate the results of this research and can be used as inputs for future research in terms of whether the continuation of the validation method is suitable or to find out if interviewing other experts would result in a similar overall feedback. In the next section, the limitations of the research is discussed.

8. 2 Research process discussion

Although the research process was successfully carried out for this study and the choices made for each phase of the research project might seem logical to the reader of this report, there were limitations to the research process despite valuable insights were gained through the research process of this study. In this section, the limitations at each phase of the research process is reviewed.

Problem identification and research focus: Due to the limitation of the study program and time constraint of the project, the selection of problem and identification of the problem was made using a simplified life cycle thinking analysis and the annual average GW data from the UNFAO database. The identified problem of GW in Uganda might not be present or as important as described in this thesis report because the area of research and the problem addressed of the graduation thesis was required to have a suitable relation to the field of Industrial Ecology.

Conceptualizations of SL, RWSD landscape and GW resource management: Due to the time constraint of the study, conceptualizations were made using biased assumptions from the author and literature material. Limited access to consult actors in Uganda WASH about how SL is carried out in Uganda, how RWSD operates in Uganda and the preferred choice of GW resource management can lead to inaccuracy of the conceptualizations in this phase. GW was modelled as a constraint; therefore, some interactions between RWSD and GW cannot be observed and the GW results could differ from reality.

Conceptualization of the designed ABM and the chosen modelling method: ABM was selected as the method of modelling in this study, and the selection was argued using literature material on the different modelling techniques considered for comparison. There are other techniques beyond the expertise of the author which were not taken into consideration when selecting the method of modelling and analyzing the problem. Due to time constraint, domain expert and actor consultation was limited at the design phase of the ABM and the designed model was simplified from how SL, RWSD landscape and GW resource management was conceptualized in the previous phase.

While simplification of the model design can lead to oversimplification and exclusion of relevant components as discussed in chapter 8, a greater level of detail on the design of the model can lead to difficult interpretation in the experimental results. The decision to include less detail from the conceptualizations made in the previous phase into the designed model was argued to be appropriate and at a balanced level of detail, because main effects were able to be distilled by the author and communicated to domain experts for preliminary validation.

Application of the model: The designed model was applied to a single case study under the spotlight of regulated rationing through the design of the experiment. As mentioned previously, there were limitations in the design process and therefore, the results of the experiment is preliminary because the model is a prototype for future implementation. Although the experiment contained different scenarios and results did reflect reality in limited ways, further insights could have been gained by applying the designed model using multiple case studies.

Validation of findings: Two domain experts were consulted during the validation phase of the study and the legitimacy of the findings generated from this research increased through this phase of the project. However, a larger sample of domain experts could have been consulted to further increase the legitimacy of findings generated from this study.

Overall research process: Although a product was made through the research process, the quality of the product can be improved through multiple iterations because the research process was only implemented once for this study.

9. Conclusion

From chapter 1, the problem of GW scarcity in Uganda was identified through a brief life cycle thinking analysis and the selected main research question of this study was: *How can social learning be conceptualized and modelled for GW rationing in Uganda's rural domestic water service delivery?* The main research question was answered through the designed agent-based model; however, conceptualizations of social learning, the rural water supply delivery landscape in Uganda and the GW rationing method was made prior to the design of the agent-based model. Social learning was conceptualized using memetics, selection, variation and replication based on Knipschild's (2016) work. The rural water supply delivery landscape was conceptualized using the socio-technical system perspective and multi-level governance. Due to the lack of expertise and the exclusion of the environmental dimension in the socio-technical system perspective, GW was conceptualized as a constraint within the technical dimension of the conceptualized system. GW rationing was argued to be possible under the multi-level governance perspective in Uganda and was conceptualized to restrict the amount of water allowed for withdrawal at a hand-pump water point by calculating the expected amount of users. Simplification of the conceptualizations and assumptions were needed to translate the above mentioned conceptualizations into the agent-based model due to the time constraint of the study.

The designed model was applied to a case study in Uganda and domain experts were consulted to ensure the conceptualizations used in the model and the outcomes of the case study were suitable to the study and reflect reality. Under the influence of social learning, multiple patterns about GW levels and water service levels emerged from the application of the model. As population growth rate and water point growth rate increase independently or concurrently, GW depletion rates increased due to the assumptions made in the design of the model. GW performance increased as ration ratios decreased and GW performance was influenced by different social learning styles as a result of ration ratio knowledge exchanges. Network connectedness theory was used to explain why GW performances were influenced by the different social styles and the exchanges of ration ratios. Highly connected and steady learning networks performed the best from the case study, because the diffusion and accessibility of high quality memes was possible within the above mentioned network structure. The importance was network connectedness over steadiness was shown from the case study through the different social learning styles for Uganda's rural water supply delivery under GW rationing. Ration ratios were approaching zero over time in the simulation leading to undesired water service levels for water users as well.

Despite the simplifications and assumptions made for the designed model, the designed model, conceptualizations, assumptions and findings from the case study were valid and reflected behaviours under critical situations in reality. Under non-critical situations, decision making and learning of ration ratios includes water service levels performance and other factors beside GW performance. The model results also reflected rationing from an informal perspective where rationing is in place without regulations. Based on the findings from this research and case study, recommendations were made and are discussed in chapter 10 of this report.

In conclusion, GW depletion rates can be reduced through social learning and rationing. The

application of social learning under the preferred network structure can increase the sustainability of GW resources and water security. However, when the intensity of rationing is determined only through the consideration of GW performance, undesired water service level can surface as water users are required to travel farther distances to collect enough water and are forced to use alternative water sources such as an unsafe source. Including a constraint within the technical dimension of a socio-technical system was suitable to conceptualize rural water service dynamics for the study; complex environmental dynamics can be avoided at the cost of increased uncertainty when information about the environmental dimension is limited. The use of memetics, selection, replication, variation, multi-level governance and GW rationing was suitable to represent social learning and Uganda's rural water service delivery landscape in the context of this study. Environmental strategies can be diffused or emerged through social learning to address other sustainability related issues where the application of (new and innovative) technical solutions is limited; however, environmentally focused strategies can lead to detrimental effects in other areas in reality and should be taken into account when strategizing for the environment to ensure sustainability in the area of interest.

10. Recommendations

According to the findings and validation discussions made from this study, recommendations were made at three different levels: model improvement, future research directions and Uganda water services.

10.1 Model improvement recommendations

As mentioned previously in chapter 8, the designed model excluded or oversimplified several components from the actual situation in Uganda. First, the model can be improved by adding WP placement behaviour. The suggested change to the model in this regard is to place another WP agent in a nearby proximity when a designed threshold is reached at a given WP agent to reflect crowding and WP placement behaviour in reality. Crowding at a WP can be further represented in the designed model by setting a limited amount of WU allowed to visit a given WP agent.

Geographical, hydro-geological and population placement characteristics of the rural areas of Uganda can be added to improve the design of the model. Characteristics such as rivers, roads, mountains, macro migration behaviour, birth rates and death rates can be added to the model when the level of detail is considered insufficient. Hydro-geological characteristics can be included in the design of the model according to how the ministry of environment in Uganda conceptualized GW recharge rates based on different regions in Uganda in the national water assessment report.

Adding learning behaviour at the WU level can improve the designed model as well; where WU will go directly to the WP where there is a higher volume of water allowed to be extracted due to rationing or directly visit the unsafe type WP after learning they have to visit a certain amount of WPs overtime. This is because in reality WUs do learn from experience and learn from the word of mouth.

The DLA agent's decision making phase is another area in the designed model suggested for further improvement based on the feedback of the consulted domain experts. The decision making sequence can be further detailed by placing an additional sequence where collective pressure to change GW withdrawal rates is possible between DLA agents of each district and adjusting the GWL to be a unified unit across districts rather than as separate units. The described improvement can be further improved by making DLA agents take WSLs into account when deciding GW rationing rates. This also calls for an adjustment to the structure of the meme, how GWL and aquifers are conceptualized and how DLA decides whether or not to learn and apply ration ratios. Ration ratios and GWL should remain within the meme, and the total GW withdrawn from improved type WP in each district should be shared as well.

Lastly, the model can be improved by including relational and network forming agents and activities. Since the SL network was assumed to be formed and conceptualized using Knipschild's (2016) method of FR, myopic and random, the designed model can be adjusted to have only a few existing connections between districts and information broker agents in the model to further simulate reality without the three preset SL styles. The network can be

formed through a designed relational sequence where DLA agents decide to participate in SL activities and relational activities based on the GWL performance, motivation and knowledge about sustainability. Motivation can be represented as a ratio between the level of GWL performance and knowledge, and knowledge can be influenced by information broker visits and SL activities. Relational activities can be carried out by highly motivated agents to increase the probability of meme transfer and application. In other words, the learning and application of the meme also depends on whether trust is formed between the sender and the receiver of the meme.

10.2 Further research recommendations

Recommendations for further research were made based on the insights gained and research process carried out as presented in the previous chapters of this report. The recommendations for future research were categorized into three different directions: further research required to implement the recommendations made for model improvement, validation of findings and general research areas.

Future research directions to investigate for model improvement include the study and conceptualization of: WU water collection behaviour in rural areas; decision-making and SL behaviour under non-critical situations when decision makers have to make decisions based on WSL, WP placements, financial allocation GWL and personal political agenda; how SL networks and relational activities are formed and occur in Uganda; the local hydro-geological characteristics and the local population characteristics. The application of SES can be more suitable to conceptualize the RWSD landscape in Uganda when hydro-geological characteristics are included in the model. A brief description on how to conceptualize Uganda's RWSD as an SES could be found in Appendix D.

In terms of validation of findings, future recommendations include: applying the designed model into another RWSD system in another landlocked country, performing the experiment with more repetitions of each model setting combination and performing a sensitivity analysis using statistical methods such as Monte Carlo. Increasing the repetition of the experimental trails and applying the model to another case study in a different landlocked can further reduce the probability of a misleading pattern emerging due to the different designed components which rely on randomness. However, it is recommended to revisit the assumptions of the study and the designed model to ensure the accuracy of the results. Since the model was designed to be highly dimensional, the use of the t-distributed stochastic Network Embedding (t-SNE) data analysis method was recommended to collapse high dimensional outputs into a lower dimensional space. Applying the designed model to another landlocked country in Africa allows the findings to be compared and generate further insights.

Lastly, future recommendations for general research practice include: exploring the effectiveness of applying GW rationing in domestic water use in comparison to GW ration for industries in Uganda and exploring how GWL and WSL react to other GW resource management strategies in comparison to GW rationing for Uganda's RWSD. The insights gained from this study could also be transferred and applied to other similar sustainability related problems and analysis; as well as other analysis for policy making in a similar context. The research direction of exploring the effect of SL has on GWL when SL is applied

concurrently for WSL and GWL management in Uganda is an example of a future research direction where the insights from this study can be transferred for further research or applied as one of the inspirations for the propose of the research.

10.3 Recommendations for Uganda's RWSD system

Five recommendations were made based on the insights gained from this study for Uganda's RWSD system. The recommendations were categorized into social dimension and technical dimension related suggestions.

10.3.1 Social dimension recommendations

Organizing the learning network towards a highly connected and steady manner is the first recommendation for Uganda's water service delivery. Using hand pump mechanics in Uganda as an example (Magara, 2014), starting a learning association for GW management can be useful to prove its legitimacy as a profession in aiding the development of RWSD and increasing water security to the national level governmental authorities. Lobbying WASH sector actors in the political landscape in Uganda can help the association to gather more members and in proving its legitimacy. By creating an association, the network and the practice of learning can be regulated and standardized to increase the steadiness of the learning network. Allocating funding from the national government to the association can help the association to expand and gather more members or setup more learning sessions to increase the connectedness of the learning network. This way learning for GW management can be standardized and regulated to increase the performance of resource management as local solutions can be diffused as well along with the solutions made from the national level. The above recommended activities were made because findings from this study have shown the structure of the can affect the performance of GWL and WSL; and the structure of the network should be formed towards a FR style for best performance.

Besides organizing the learning network in Uganda, rationing of GW for rural domestic users and industries is the second recommendation derived based on the insights gained from this study. In general, GW rationing for rural WUs is not recommended as the only GW resource management solution because meeting national WSL targets will be difficult; however, rationing of GW at current WPs during the rain season might be one of the ways to stimulate WUs and industries to seek other water sources for their needs. Along with policies which promote other water supply sources, the probability of WUs selecting unsafe water sources while seeking other water sources during ration can be reduced. Placing fines, tariffs and taxes on industries which rely on GW resources are suggested policy strategies to investigate further for GW rationing; and the author's personal suggestion on how GW rationing could be implemented for industries can be found in Appendix P. According to Figure 1 and Owori (2007), the agricultural industry is the second largest consumer of GW and one of the main source for many rural Ugandans; therefore, rationing for industries should be further investigated before implementation to avoid unwanted economic or other effects.

GWL performance should not be the only deciding factor when applying and setting the rationing percentage is the third recommendation made for this study. WSL and other behaviours should be taken into account when setting the rationing percentage for WUs to

avoid extreme results as shown in this study.

10.3.2 Technical dimension recommendations

Increasing the frequency of GW assessments, monitoring and diffusion of the results was the fourth recommendation for Uganda's RWSD system to ensure water security in each district and create awareness of the problem in Uganda. This recommendation was to avoid forcing decision makers to ration GW resources to such extremes leading to undesired WSLs as shown in this study in the future.

The last recommendation is to diversify the RWSD infrastructure to relieve pressure on GW resources and to increase water security because the RWSD infrastructure heavily depends on GW resources. Rainwater harvesting (RWH) is recommended to diversify the RWSD infrastructure to prevent and during the occurrence of extreme GW scarcity situations. According to the brief LCA made for this study, surface water is another renewable water source in Uganda. Surface water in the FAO database was defined as the water collected in lakes and rivers during rainfall. Since surface water is considered as an unsafe source in Uganda, WUs and water suppliers can harvest water from the source of surface water (rainwater) in the water cycle to address the water demand in the rural while diverting GW pressure and increasing WSLs. The recommendation of RWH was suggested by domain experts during the consultation interview. The author's personal suggestion on how to diversify the RWSD infrastructure in Uganda using RWH and how to address the current problems with RWH in Uganda is located in Appendix P.

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Appendix A: Life cycle thinking (LCT) analysis

How the author identified this issue will be explained through the insights gained from examining existing practices, GW flow cycle in section, and the potential effects of GW depletion in Uganda.

A.1 Examining existing practices for GW sustainability with regards to RWSD

The LCT analysis began with examining official Ugandan government documents to find out whether withdrawing GW for domestic use is a sustainable practice. It is a way to find out whether GW withdraw is sustainable for domestic use in the rural areas of Uganda. The reason why this method is chosen was because of the following arguments:

1. There are governmental ministries and directorates dedicated to GW management, demand, and supply and official reports are released from those institutions
2. One of the directorates, Directorate of Water Resources Management (DWRM), is responsible for issuing permits for GW extraction and drilling to registered companies for RWSD, and these companies are obliged to submit hydro-geographical data every 3 months for review (MetaMeta, 2010)

A literature search about whether withdrawing GW for domestic use is a sustainable practice returned with the following result from the Ministry of Water and Environment of Uganda (MWE): The MWE suggested GW supply could meet future domestic rural water demands (MWE, 2013). An explanation was given by the MWE on how the result was reached and it is discussed below.

The ministry of water and environment of Uganda (MWE) compared the demand for domestic water use in rural areas and small towns against the estimated amount of renewable GW resources (MWE, 2013). Such comparison is a practice for GW sustainability, because it serves as an indicator for actions if the demand is higher than the amount of renewable GW from the water cycle input. The report suggested the current and future demand for domestic water purposes in rural areas and small towns of Uganda could be safely met by GW (MWE, 2013). This conclusion was made based on an assessment between projected demands up to 2030 and the estimated amount of renewable GW resource. Renewable GW (SGW) was calculated by the following equation in the assessment (MWE, 2013):

$$SGW = \frac{TR}{SF * BF}$$

Equation 1: Sustainable GW equation as presented by the ministry of water and environment in Uganda (MWE, 2013)

Where *SGW* represents the amount of GW which are renewable, and therefore the amount suitable for withdraw to satisfy domestic water demand in a particular geographical area, *TR* represents the total amount of GW recharge, *SF* represents the safety factor and *BF* represents the sustainability factor. *SF* and *BF* were implemented to address

two different types of uncertainty. The intended use of SF was to address the uncertainty of TR, it prevents the use of a large value for TR to increase the amount of SGW (MWE, 2013). The implementation of SF also address local inconsistencies, as the study was made to address three different sets of geographical and geomorphological characteristics (MWE, 2013). The intended use of BF was to prevent unacceptable levels of environmental damage due to GW extraction. The value of TR was derived based of the value of the base flows of low flow rivers in Uganda (MWE, 2013), because the low flow of rivers mainly depend on GW draining into them to sustain itself (MWE, 2013); and therefore it was assumed that the stream flow of low flow rivers equals to GW recharge minus some losses (MWE, 2013).

However, uncertainty surfaced when double checking this insight from MWE with other literature. A study by Mölg, T., Georges, C. and Kaser, G in 2003 concluded that GW resources are declining. Besides the above mention study, another study by Nsubuga, Namutebi and Nsubuga-Ssenfuma in 2014 also shown a surface area reduction in lakes using data from the Ministry of Water Resource of Uganda and multiple citations of GW resources declining (Nsubuga, Namutebi & Nsubuga-Ssenfuma, 2014). One of the reasons for this decline was said to be unsustainable withdrawals of GW (Nsubuga, Namutebi & Nsubuga-Ssenfuma, 2014). Since the lakes are interconnected by rivers in Uganda (Nsubuga, Namutebi & Nsubuga-Ssenfuma, 2014), and rivers are connected to GW resources, the suggested SGW presented in the MWE report remain questionable and require further investigation.

This is because if GW resources and rivers levels are declining, the practice of GW withdraw could be considered unsustainable even if the amount of SGW for withdraw is below the value of TR. In this case, it was hypothesized that the actual value of TR is zero or extracting more than the value of SGW for this phenomenon to occur. The latter was ruled out because GW withdrawals are mostly regulated, mentioned in argument #2 of this section. GW resources and river levels should be maintaining a certain level or raising if the practice was considered sustainable. GW withdrawals for domestic use account for about 51% in the country in 2008 (Nsubuga, Namutebi & Nsubuga-Ssenfuma, 2014), and therefore making GW security an important issue that needs to be addressed for the WASH sector with regards to the sustainability of WSLs, ethical sustainability and environmental sustainability.

A.2 GW flow cycle

In the previous section, the literature analysis from MWE suggested GW supply could meet future domestic rural water demands (MWE, 2013), while other research literature sources suggested otherwise. This uncertainty led to further investigation and the gained insights will be discussed in this section.

In order to address the uncertainty and the hypothesis presented in the previous section, a GW flow cycle analysis was performed to identify the inflows and outflows of GW in the country of Uganda. Instead of only looking at the amount of TR as a main factor (inflow) to derive SGW in the equation presented by MWE, the outflows of from the amount of TR, total outflows from recharge (TOFR) is also included in the equation to derive SGW from the natural cycle. By doing so, a more accurate value of SGW could be obtained. The new SGW value would represent the amount of GW which could be withdrawn safely without changing GW levels and the amount of GW available for a sustainable practice of RWSD. Since this was a brief LCT analysis, the equation was simplified due to time constraint for examination; and the equation used for the analysis was as follows:

$$\text{SGW} = (\text{TR} - \text{TOFR}) / (\text{SF} * \text{BF})$$

Equation 2: Suggested sustainable GW equation to use for this study

The data examined from the Food and Agricultural Organization of the United Nations' (FAO) database AQUASTAT, suggested the value of TR holds true at around 10% of the total annual rainfall within the country from the MWE report (FAO, 2014). On the other hand, AQUASTAT also stated that 100% of the GW recharge drains into river streams and forms the base river flows in Uganda (FAO, 2014). This is due to the fact that Uganda is a humid and landlocked country (FAO, 2014). The data suggested that there is no GW recharge from annual precipitation within Uganda (FAO, 2014). Sudan, Tunisia, and Togo are examples of nearby countries where AQUASTAT have shown a positive value for GW recharge (FAO, 2014). The GW recharge and GW recharge outflows values observed in the AQUASTAT database is documented in Figure 24.

	Surface water produced internally (10 ⁹ m ³ /year)	Groundwater produced internally (10 ⁹ m ³ /year)	Overlap between surface water and groundwater (10 ⁹ m ³ /year)	Total internal renewable water resources (IRWR) (10 ⁹ m ³ /year)
Sudan	2 (2014)	3 (2014)	1 (2014)	4 (2014)
Togo	10.8 (2014)	5.7 (2014)	5 (2014)	11.5 (2014)
Tunisia	3.1 (2014)	1.495 (2014)	0.4 (2014)	4.195 (2014)
Uganda	39 (2014)	29 (2014)	29 (2014)	39 (2014)

Figure 24: Renewable GW in Uganda, Sudan, Tunisia and Togo from United Nations' AQUASTAT database (FAO 2014)

In order to demonstrate the modified equation could yield a positive and desired result (a positive value), the equation was applied to a nearby country in Africa. From the example shown in Figure 24, the values were taken from Togo and resulted in a positive amount of

renewable GW which could be extracted in a sustainable manner. A comparison between the two countries resulted Uganda does not have any SGW, as shown in Figure 24. In this example, SF and BF were assumed to be a product of 1, because it is impossible to go below 1 (doubling the amount of recharge in the case of 0.5), and the goal of this analysis was to find out the maximum potential of SGW of both countries.

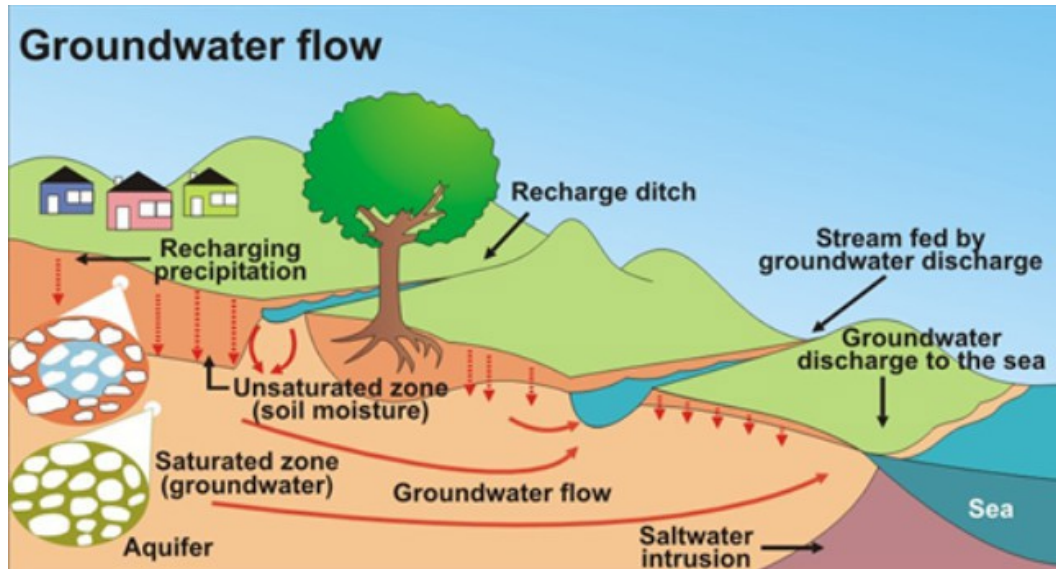


Figure 25: General GW flow diagram (ATSDR, 2011)

There are other sources of GW recharge within the GW flow cycle which was excluded from the equation. These sources are the recharge flows from having surface water seeping back into GW storage and artificial recharge as shown in Figure 25. Those were excluded because the data from AQUASTAT suggested there are negligible amount inflows from seepage and there is a declining water level trend in rivers and lakes across Uganda as well (MWE, 2011). A literature and AQUASTAT database search on the amount of artificial GW recharge in Uganda returned nothing, however it was suggested to be implemented (UNESCO, 2013).

Another factor which could influence the GW cycle is climate change. Uncertainties arose when climate models were indicating a 7 percent decrease or 14 percent increase of rainfall by 2030 compared to 1970 to 1999 average (USAID, 2012). In the case of increasing rainfall, this could be beneficial to Uganda; however, there's also the option of rainfall decrease. Since the analysis was executed to find out the current situation in Uganda, this was neglected. If the analysis was to be executed for future situations in Uganda at the time of this thesis, the latter option would be taken as a precaution.

After examining a range of difference sources of flows in the GW cycle for the modified equation, the problem of GW scarcity was identified and remains despite the fact that the MWE of Uganda announced the amount of SGW suitable for domestic use from the insights explained in this section. In the next section, a brief explanation of the effects GW depletion could lead to will be given.

A.3 Effects of GW depletion

In the previous section, the problem of GW scarcity in Uganda was identified and discussed. In this section, the effects of GW depletion will be discussed briefly as it is outside of the scope of this thesis project, yet relevant for this problem analysis.

In terms of RWSD, this is alarming as WSL could drop with regards to the quantity characteristic, because of GW depletion and the sustainability of the service could be hindered in the future. In a service infrastructure where about 80% of the technology used to provide improved sources of water depend on GW (MWE, 2018), and where 80% of Uganda's total population are currently living in rural areas, the sustainability of water security in terms of quantity and quality is one of the major effects from GW depletion for RWSD.

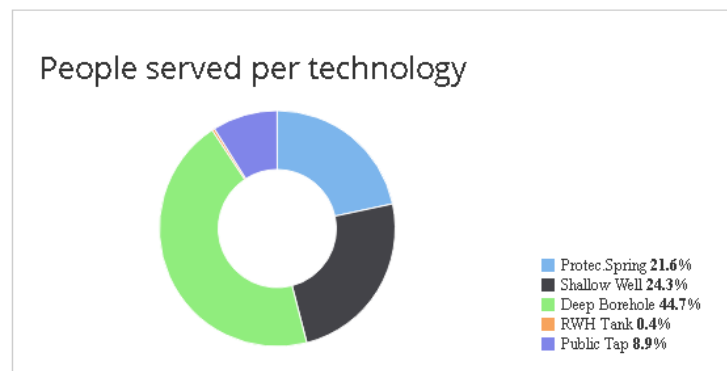


Figure 26: People served per technology (DWD, 2017)

However, according to the MWE report, volumes of GW extracted within the suggested SGW estimates are within a range of acceptable consequences (MWE, 2013). The content of what these consequences were and how they were considered acceptable were not documented in the report by MWE. From the calculations shown in Figure 26, it was concluded that there are no SGW, meaning the amount of GW extraction exceed the suggested SGW estimates. Therefore, it could be considered unacceptable in this analysis. Since the content of what these consequences are for Uganda was not included in the MWE report, a general explanation is given below to demonstrate the potential effects from GW depletion.

In general, GW over-exploitation leads to water insecurity, water quality degradation, and loss of habitat and biodiversity due to the impacts towards streams and wetlands (Sophocleous, 2009). Considering a portion of Uganda's power supply structure depends on hydro-powered infrastructure, the lowered levels of stream could affect power generation, leading to power rationing and disrupting economic activities (USAID, 2012). Lowered GW levels could also cause a change in the underground geological structure, increasing the possibility of sinkholes to occur (USGS, 2016). Sinkholes could cause accidents to occur and infrastructure damages due to changing surface landscapes (USGS, 2016).

Appendix B: Background information on social learning

B.1 Who learns

SL occurs in individuals and in groups; therefore, the individuals and groups involved in the SL process could and do learn. Groups could be further described as organizations and institutions within a system boundary. These different levels (individual, organizational, institutional) are nested in each other, meaning they could learn from each other (Knipschild, 2016). Individual(s) are embedded in an organization and institutions are made up of organizations. Individuals could learn from other individuals, organizations and institutions; organizations could learn from other organizations, individuals and institutions; and institutions could learn from other institutions, individuals and organizations.

B.2 What is social learning at the individual level

Social learning was first defined by Albert Bandura (1977) at the individual level to contain the following characteristics (McLeod, 2011):

- 1) Mediating process – The process contains four elements:
 - a) Attention – Learning starts when one is exposed to or notices something worth remembering
 - b) Retention – Refers to how well the content was remembered, if one forgets what they have learned, one cannot replicate it
 - c) Reproduction – Refers to the physical ability to perform what one has learned
 - d) Motivation – Refers to the will to perform what one has learned. One is more likely to perform what they have learned if one perceives the pros of performing what they have learned outweighs the cons.
- 2) Observational learning – learning also occurs when one is observing; operant conditioning applies to observational learning as well.

There are three different approaches to understanding learning: behaviourism, cognitive science, and experiential learning (Knipschild, 2016). The behaviourism perspective describes learning as responses to stimuli, and there should be an observable change in behaviour when learning occurred. In cognitive science, learning is described as the absorption of information from the environment, where one will mentally sort it afterwards, and finally applying this information to activities (Knipschild, 2016). Experiential learning describes learning as a process of translating experiences into knowledge (Knipschild, 2016). While social learning belongs in the school of cognitive science, it translates how stimuli and response is interpreted in the cognitive perspective (Knipschild, 2016). Reciprocal interactions between cognitive, behavioural, and environmental influences is how one could explain human behaviour under the theory of social learning (Knipschild, 2016). Bandura argued that because there is a cognitive process, learning is not purely behavioural (Knipschild, 2016). Bandura agreed one could learn using classical conditioning and operant conditioning

theories in the school of behaviourism by Watson (1913) and Skinning (1948) respectively (McLeod, 2011). However, Bandura added one could also learn by observing a behaviour and the consequences of the behaviour besides learning by classical conditioning and operant conditioning (McLeod, 2011). Learning could also occur when one observed, and the extracted information undergone a mediating process from those observations. Operant conditioning guidelines apply to social learning as well, where learning is affected by the central concepts of operant conditioning: punishment, reinforcements, and neutral operants (McLeod, 2007). These operants are used after a behaviour or response has been made. Learning occurs through experiencing these stimuli. Reinforcements are used to increase the probability of a behaviour being repeated, punishment is used to decrease the probability of the behaviour being repeated, neutral operants neither increases or decreases the probability of the behaviour being repeated (McLeod, 2007).

There are two types of reinforcements: positive and negative (McLeod, 2007). Positive reinforcement increases the probability of a behaviour being repeated, through providing a consequence an individual finds rewarding after the behaviour is performed (McLeod, 2007). Negative reinforcement increases the probability of a behaviour being repeated, through removing a consequence an individual finds unpleasant after the behaviour is performed (McLeod, 2007). Punishment decreases the probability of a behaviour being repeated, through applying an unpleasant consequence or removing consequences where one finds rewarding (McLeod, 2007). However, when punished behaviour is suppressed, it will resurface once a punishment consequence no longer applies (McLeod, 2007). Punishments also cause increased aggression and create fear towards certain stimuli (McLeod, 2007). Punishment only informs one what not to do, which does not necessarily guide one towards desired behaviour; unlike reinforcements, where it teaches what one should do (McLeod, 2007). Therefore, reinforcements and punishments contributes to affecting the mediating process in social learning.

B.3 What is social learning on a multi-individual level

In the previous section, Bandura's theory on how social learning occurs at the individual level was explained. However, social learning could also occur on a multi-actor level. While Bandura's SL theory on how individuals learn still applies when one is in a multi-individual setting, other distinguish features of SL arise when learning in groups as well and are as follows (Beers, Sol & Wals, 2010):

- 1) voicing one's understandings
- 2) interpreting others' contributions
- 3) negotiating a new understanding of a learning task or problem
- 4) the newly negotiated understanding should reflect a shared understanding between the individuals involved
- 5) all of the above features should be iterative-based

Elements of the Bandura's theory of SL are translated into actions which demonstrate how SL occur in a multi-actor setting. When one is voicing their understandings, others are learning through observing in a multi-actor setting. Voicing and negotiating reflect reproduction, as one needs to have the ability perform what was learned for these activities to occur. Interpretation

reflects retention, as one needs to remember what the others have voiced and negotiated previously to make sense of what was learned. The new and shared understanding(s) can be interpreted as the product of what was learned from the SL process in a multi-actor setting. Attention and motivation are assumed to be positive when one is participating in SL in groups.

Due to the iterative nature of these distinguish features listed above, SL in groups could be seen as a process and the product (what was learned) evolves over the process. Evolution occurs under SL in groups, because learners construct their own knowledge iteratively and collectively as a group through voicing, interpreting and negotiating with the help of facilitators, instead of having instructors giving their knowledge to learners (Beers, Sol & Wals, 2010). Thus, the role of the teacher changes under SL in groups, and a facilitator's role is to support learners with tools to construct their own knowledge rather than only providing knowledge (Beers, Sol & Wals, 2010).

From the field of learning sciences, the processes of how individuals learn under the theory of SL in a group setting and individually was explained. In the next section, the process of how SL is applied in the professional field of sustainability sciences will be discussed.

B.4 Applying social learning in sustainability sciences

In the previous section, the process of social learning in an individual was discussed at the individual and group level. This section will explain how SL is interpreted and applied in the field of sustainability based on the understanding of SL previously. The understanding of such processes could provide insights to how GW levels could be affected through SL.

Since environmental problems are complex due to its multi-dimensional nature (social, economic, technical and environmental dimension) (Pahl-Wostl, 2002), learning of such complex problems are through SL and take place in groups with members of both diverse and specific backgrounds (Beers, Sol & Wals, 2010). Traditional learning sciences focus on understanding the process of how social learning occurs in an individual or a group, however, sustainability sciences focus on how to utilize SL as a process to solve complex environmental problems while concepts of SL from learning sciences still applies. From the perspective of sustainability sciences, complex environmental problems are becoming increasingly high risk and uncertain, and could be addressed through SL by influencing the decisions made about environmentally positive actions. In other words, sustainability sciences focus on the design and execution of SL activities to solve complex environmental problems. The combination of such activities are considered as a process. Essential elements which are critical to have within processes of SL applied in resource management, through the SL activities carried out in order for SL to be effective are defined as follows (Pahl-Wostl, 2002): “

- Build up a shared problem perception in a group of actors, in particular when the problem is largely ill defined (this does not imply consensus building).
- Build trust as base for a critical self-reflection, which implies recognition of individual mental frames and images and how they pertain to decision making.
- Recognize mutual dependencies and interactions in the actor network.

- Reflect on assumptions about the dynamics and cause-effect relationships in the system to be managed.
- Reflect on subjective valuation schemes.
- Engage in collective decision and learning processes (this may include the development of new management strategies, and the introduction of new formal and informal rules).”

A shared problem perception is referred to as a “frame”, and it is the most important SL product (Beers, Sol & Wals, 2010). This is because shared frames are constructed from an integration of knowledge, values and interests from multiple actors; and shared frames enables joint action between actors within a SL group to address challenges (Beers, Sol & Wals, 2010). Knowledge, values and interests of the actors involved in the frame construction phase are influenced and evolves through out this part of the SL process. This is because actors are engaging in an iterative process of comprehending and apprehending information by one voicing their understandings and shaping the frame through negotiation. This phase reflects how all of the distinguish features of SL mentioned in B.2 and B.3 is transposed into practice in the field of sustainability.

At the individual level, frame construction allows one to undergo observational learning from Bandura's theory. The act of one voicing their information allows others to learning during this process, and by receiving information feedback from those who learned, the one who voiced learned as well. Levels of attention, motivation, retention, and reproduction might be influenced through these exchanges, as one's attention and motivation could be stimulated through being exposed to and learning information from another. Hence, retention and reproduction could be influenced through the information one has received or through increased levels of attention and motivation. Since operant conditioning apply to social learning as well, this would be done through the exchanging of information in the frame construction phase. As one is voicing their information, the feedback one receives from the SL group will indicate whether one would receive a reinforcement, neutral or punishment signal. These signals are usually in the form of information in this phase when those who were receiving the information have reacted to what one has voiced. Those who are on the receiving end of the information would receive these signals as well, because when one is exposed to the voiced information, one would go through cognitive processing of the information. Through the interaction between the received signals, learning occurs under Bandura's theory on SL.

The iterative cycle of these exchanges also contain all of the distinguish traits of SL in a multi-individual level. This is because the elements of voicing, understanding others and negotiating are part of the activities during frame construction. A frame reflects the product of a shared understanding of information through a series of information exchanges and learning, of which it is another distinguish trait in multi-individual level SL. A frame could be adjusted overtime as the process of framing is iteratively performed as information is processed in the same phase, or through learning of the results from other activities in the other phases mentioned below.

Reflecting on assumptions and subjective valuation schemes puts the SL group into an iterative cycle of reconstructing the frame, leading to continuous learning and problem solving ability. Engaging in collective decision and learning process includes co-development and applications of solutions, and form the bases for reflecting activities as it generates data and new information for actors to iteratively learn in the SL group. During these above mentioned activities, learning at the individual level and multi-individual level undergo similar processes as mentioned in the previous paragraphs about frame construction in this section.

Engaging in collective decision and learning processes, reflecting on assumptions and subjective valuation schemes and building up a shared problem frame are considered problem solving activities in the SL process. However, the SL process applied in sustainability sciences also contain relational activities. Building trust and recognizing mutual dependencies are relational activities involved, as these activities address mutual distrust and cultural differences between actors in a SL group (Beers, Sol & Wals, 2010). Relational activities ensure commitment from actors in a SL group by creating a shared sense of problem ownership and shared responsibilities if successful (Beers, Sol & Wals, 2010). Self-governing capacities could be increased as well through relational activities (Beers, Sol & Wals, 2010). In other words, relational activities are meant to increase the chances of improving the quality of the mediating process (attention, retention, reproduction and motivation), and to ensure the distinctive elements in multi-individual level SL could occur.

However, the above discussion on the definition of SL in this section excluded an important element in the SL process in sustainability science; which is the formation of the SL group or network at the beginning of the SL process. A SL group or network must be formed before problem-solving and relational activities can take place. Diversity of SL groups is an important factor as well, as diversity contributes to performance (Beers, Sol & Wals, 2010). Diversity refers to actors with different knowledge, values and interests in a SL group, and should be present because diversity enable actors to voice, negotiate, interpret construct knowledge or frames for joint action (Beers, Sol & Wals, 2010).

From this section, the overall process of SL was discussed under the scope of how is SL applied in the field of sustainability. The learning processes and activities used in the field of sustainability were explained through academic literature. In the next section, an explanation will be given on how SL influence sustainability.

B.5 The influence of SL in sustainability

In the previous section, the learning processes and activities of SL was discussed in the perspective of sustainability sciences. As mentioned before, SL is applied to solve complex environmental problems in general practice, and the insights of how SL contributes to sustainability by solving complex environmental problems have yet been discussed. In this section, an explanation will be given on what these insights are.

Before an environmental action or solution take place, a decision is made on what to be performed. The decision making process is the targeted area of which the effect of SL occurs. In this section, an explanation will be given on how SL influences the decision making process in sustainability practices with an example.

In order to understand SL's influential phenomenon on decision making, a basic assumption is made where decisions are normally made under classical decision theory (Pahl-Wostl, 2002).

Classical decision theory (CDT) conceptualize decision making as a rational choice made from a set of clearly defined alternatives (Pahl-Wostl, 2002). In other words, decision makers must learn factual knowledge about their sets of alternatives before deciding on the best option. Consider a decision maker working on a simplified climate change problem as an example (Pahl-Wostl, 2002), and the decision maker needs to decide on a measure to address the climate change problem. There are three options available for choosing and each option has their associated costs with them (Figure 27). If the decision maker chooses option 1, the initial cost of implementing this option would be 60 Euros, and one of the uncertain consequences (in this example would be the unchanged global temperature) is eliminated together with the costs associated with the particular consequence. However option 1 contains uncertainty, and this uncertainty is addressed with (weighted) probability of a fifty percent. The probability represents a chance of another consequence occurring (the possibility of global temperature increasing, $\Delta T=1^{\circ}\text{C}$). If this consequence does occur due to the decision made to proceed with option 1, the cost required for the consequence is 100 Euros. Therefore, the total cost of option 1 would be 110 Euros and calculated as follows: $110 = [(0.5 \times 0) + (0.5 \times 100) + 60]$. In a rational situation, the decision maker would choose the cheapest option to address the problem, which is option 2 in this example.

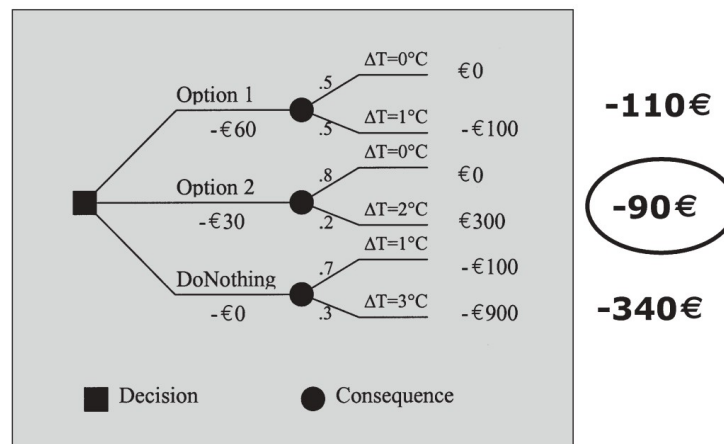


Figure 27: Classical decision theory (CDT) example from Pahl-Wostl (2002)

There are a few ways SL could influence decision making based on the classical decision theory in the example, the construction of a fourth option being one of them. The SL process enables sharing of knowledge through activities, and new knowledge could be constructed leading to a new option available which could be better than the previous options; or the newly constructed knowledge changes the effect of the consequences; or the reconstruction of knowledge leads to a point where the need for a decision in the original context no longer exists. Although CDT states that the alternatives should be well defined and these alternatives are often factual knowledge for a decision to take place, the SL process could provide an opportunity to redefine those alternatives and the consequences. Thus, the process of social

learning can be combined with CDT in sequence (Pahl-Wostl, 2002).

An example in this regard would be the construction of a new frame, or new factual knowledge constructed upon those alternatives. However in the practice of sustainability sciences, environmental problems often contain high risks with high uncertainty. This means frames and or alternatives are constructed based on uncertain and controversial knowledge. The best possible option is no longer available to decision makers from factual knowledge alone (objective) due to high uncertainties, and the best alternative could be argued with different points of views (subjective). In this case, a decision is still needed because of the high stakes on the problem. Thus, the SL process provide opportunities for decision makers to construct their own version of the “best” decision and decision making is influenced by the different point of views and knowledge during the process. Aside from constructing the “best” decision, the SL process also provides actors with legitimacy. Due to the subjective nature of the knowledge decision makers used to make a decision, legitimacy is built from the SL process and could be useful as input to influence other decisions.

From this section, the overall effect of SL was explained in terms of how SL brings change and tackle environmental problems. By influencing the information a decision maker receives through the process of SL, one could make an optimal decision for sustainability by increasing alternatives, removing alternatives or reconstructing the product or consequences of an alternative. In the next section, the discussion continues on what could be learned of which the adjustments to the decisions and consequences could be based upon.

B.6 What could be learned within the SL process?

From sections B.4 and B.5, SL was described as a method to influence decision makers on decision making to tackle environmental problems. In this section, the types of information or skills one could learn through the SL process in order to influence decision making will be described. There are different types of knowledge of which one could learn under SL through different activities. These different types of knowledge will be discussed in this section. What could be learned from SL processes can be broken down into four competencies, four components, and three different loops in general. Beginning with competencies, there are four different defined competencies and are listed below (Knipschild, 2016):

“ Technical competence: concerned with analysis and solving a problem of a technical nature

Management competence: concerned with the need for adequate pool of resources

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 competencies, concerned with the deliberate efforts to learn and innovate”

The technical, management, and governance competencies could be learned through experience and practice (Knipschild, 2016). The competence for continuous learning and innovation could be learned through monitoring and developing the other three competencies,

this competence is about learning how to improve learning efficiency in the other three competencies (Knipschild, 2016). These competencies are applicable to individuals or groups; however, the technical competence, management and governance competencies could be further described with four components when applied to only at the individual level [Knipschild, 2016]:

“Cognitive-explicit component: concerned with the use of information or objective and replicable theory

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

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

Components and competencies enable actors to learn in loops during a SL process. Due to the iterative nature of SL processes, learning loops explains what actors could learn from a relation between actions and feedback perspective. The learning loops are as follows (Knipschild, 2016; Beers, Sol & Wals, 2010):

Single loop learning: learning to adapt to an environment or situation through actions

Double loop learning: learning about their underlying goals, theories and strategies

Triple loop learning: learning how to learn or learning to learn in single loop learning, one learns from the actions performed for an environment or situation.

During the execution of these actions, observations are made, and the results of these actions are recorded. One would learn from the observations and results from the executed actions to adjust the strategy used for the previous situation in single loop learning. In resource management, single loop learning is considered essential for progress. When single loop learning is deemed insufficient, double loop learning is normally explored and applied (Knipschild, 2016).

Double loop learning requires one to revise underlying goals, theories and strategies used in single loop learning (Knipschild, 2016). In resource management, double loop learning is considered essential for innovation and critical appraisal (Knipschild, 2016). In the field of resource management, the combination of single and double loop learning is recommended for increasing the quality of results from learning; because single loop learning requires one to apply the results from double loop learning in practice (Knipschild, 2016). Potential lock-ins might occur over time if one only applies single loop learning, and the results from double loop learning will not be applied in practice if one only applies double loop learning (Knipschild, 2016). Triple loop learning refers to one learning to learn; and calls for a revision of underlying constants, structure context, factors, values, philosophical frameworks and or beliefs which forms the frame of reference for single and double loop learning (Knipschild,

2016).

From this section, what one could learn from SL processes was explained; however, a way to trace and measure what one has learned in the SL processes is missing in the explanation of SL. While the descriptions from the previous sections allow one to understand the outcomes of SL and how SL is performed, being able to trace and measure what one has learned would help in providing an understanding of why certain outcomes surfaced from the SL process.

Appendix C: Why Uganda's RWSD structure can be conceptualized using MLG under the author's perspective

The structure of a sector can be explained by understanding how actors within a sector are organized to perform activities. There are four categories of which actors can be organized in a sector by the government (Boons, 2008):

- “1) Actors can self-organize through interactions without external control – Self organization
- 2) Actors can self-organize and develop monitoring and sanctioning rules (self organization leading to self-governance) – Self governance
- 3) Actors can self organize under pressure of governmental legislation (self-organization with government providing selection pressure) – Private interest governance
- 4) Actors are organized under the control of governmental initiative (absence of self organization with external control) – Governance “

In self organization, actors within boundaries are organized to perform activities without external control and to resist external change pressures. External control refers to laws, regulations, or other forms of power which order actors operate within limits; and a government is normally seen as an external agent limiting the activities actors are allowed to perform without sanctioning. However, an external agent could be an entity, actor, institution, or organization other than a government with external control as well. Governance is on the other end of the spectrum, where actors are organized under external control from an external agent for the area of concern. Under governance, specific orders and goals are set by the external agent. The interactions from self organization could lead to self governance, where internal actors develop governing agent(s) for monitoring and sanctioning of activities within set boundaries. Private interest governance is where the external agent is exerting selecting pressure on the internal agents to act a certain way either through self organization or self governance without external control. Governance could also induce the other three methods of organizations and generally does not operate with governance alone (Boons, 2008). In Uganda's WASH sector, RWSD is organized under governance, because CBM was implemented in the WASH sector by the national government of Uganda since the late 1980's. The CBM paradigm organized actors in the WASH sector to help the agent with external control: the government of Uganda, to ensure natural water resources are developed and managed, as well as water services are delivered to the population in Uganda for domestic and productive purposes in a decentralized manner (Casella, van Tongeren & Nikolic, 2015). Example forms of external control applied for CBM in Uganda to organize actors would be the existing acts, and Table 2 contains a brief descriptions of these acts.

Laws and Regulations	Purpose
Water Statute of 1995	The Statute provides the framework for the use, protection, supply and management of water resources including the institution of water user associations or WSCs and devolution of water supply undertakings.
The 1997 Water Act	The Act gives details on access rights and regulations pertaining to public and private sector investments in water services. When well regulated, HPMS are key private sector actors that support CBM.
The 1997 Local Government Act	Stipulates powers, roles and functions to decentralised government units. In Essence, the Act empowers, but also gives responsibility to local authorities to oversee central government service delivery and policy implementation strategies including CBM.
The Land Act 1998	Any location of a water supply project must respect the property rights of the land owner or occupier. In relation to this a formal written consent is usually sought before construction of a water source.
The Public Health Act of 1935	The Act consolidates the law regarding the preservation of Public Health. In CBM WSCs are also responsible for ensuring Health and hygiene at the water source as well as sensitise water users on safe water handling practices. Bye-laws related to hygiene could be enacted at the community level.
The Public Finance and Accountability Act 2003	Sets legal procedures and guidelines for the financing and accountability in respect to water projects in rural decentralised settings. It therefore takes care of the need for transparency, efficiency and good governance in support of CBM functions for rural water supply and sustainability.
The Public Procurement and Disposal of Public Assets Act 2003	Sets legal standards and procedures for the procurement of supplies and works for various public water works and investments. Ideally, this Act should guide the institution of a more enabling approach to supply of spare-parts for pumps.

Table 7: Brief descriptions of different acts implemented by the Government of Uganda to organize actors in the WASH sector for CBM (Mugumya, 2017)

The roles and responsibilities are dispersed throughout the RWSD structure (using external control from the acts mentioned above) to ensure sustainable water services in Uganda, and could be categorized in five different domains: service authority, service provider, users, civil societies and international development organizations (Casella, van Tongeren & Nikolic, 2015). The service authority is legally responsible for service delivery planning, coordination, regulation, monitoring and sanctioning water service providers (Casella, van Tongeren & Nikolic, 2015). Providing technical assistance to water providers is also part of the service authority's responsibility (Casella, van Tongeren & Nikolic, 2015). The service provider(s) are responsible for daily water services, and these services include: operation, maintenance and administration of the water supply infrastructure (Casella, van Tongeren & Nikolic, 2015). Users in the context of this study are households located in the rural areas of Uganda and utilize the rural water supply infrastructure to gather water for domestic uses. Civil societies are responsible for conveying the needs and wishes of the users, and some societies are service providers as well (Casella, van Tongeren & Nikolic, 2015). Functions of international development organizations varies among different organizations, and could be seen as an entity which aids the other categories as an organization sees fit. Formal and informal arrangements between actors from the above mentioned categories are required to ensure sustainable water services (Casella, van Tongeren & Nikolic, 2015). Casella, van Tongeren & Nikolic (2015) described these arrangements as: “ policy-and decision-making processes about responsibilities and actor relationships through which the power, responsibilities, norms, values and formal agreements embedded in laws and policies are negotiated among and

implemented by the array of stakeholders, whose roles and responsibilities may overlap. ” These arrangements create an interdependent network consist of multiple actors or agents across different administrative levels (Casella, van Tongeren & Nikolic, 2015), and represents the WASH sector's structure under governance.

As mentioned previously, there are different administrative levels in Uganda's WASH sector. The combination of governance at each level forms the governance structure of the WASH sector, and therefore the structure should be observed at multiple institutional level using a multi-level governance (MLG) approach (Knipschild, 2016).

Appendix D: Brief description on how to conceptualize Uganda's RWSD as an SES

The problem of GW levels explained in chapter 1 and 3 entails an environmental system is required in the area of study as GWLs operates in the environmental dimension, along with a social system for SL to be applied in and a technical system for RWSD. As the STS framework focuses the interactions between social systems and technical systems, the interactions between systems of the environmental and social, and the environmental and technical is not included in the framework. The environmental dimension can be included implicitly in STS, either through the environment of which the system is placed in for operation or through the context of the system. Instead of conceptualizing the environmental dimension implicitly in STS, there is another type of CAS which includes the dynamics of STS, explicitly include the interactions between the environmental, technical and social systems in the framework, and suitable to use for this study. By conceptualizing the RWSD in Uganda as a socio-ecological system (SES), the dynamics between SL (social system), hand pumps (technical system) and GWLs (environmental system) could be demonstrated clearly and explicitly for further exploration. "All humanly used resources are embedded in complex social-ecological systems" (Ostrom, 2009). Thus, GW resources in this Ugandan case can be considered a complex SES. SES includes the dynamics of a STS while expanding the boundaries of the system to include environmental factors. SES operates under governance structure because governance is required to maintain resources due to users will never self-organize to maintain resources as a generally accepted theory (Ostrom, 2009). The technical system is located in the social, economic, and political settings (S) of the framework in the first tier because it is listed in the second tier (S7), the social system (multilevel governance) is located in the first tier of the framework (GS and A) and the environmental dimension (GW as a finite pool of resource) is located in the first tier of the framework as well (RS and RU). The focal action situations is composed of interactions (I) and outcomes (O) and there could be multiple actions situations in the SES framework. The interactions are guided by SL processes, and the outcomes are WSL and GWL.

Appendix E: Social learning in the proposed landscape

From section 3.2, the landscape presented by Knipschild (2016) was adjusted for this study; however, whether SL remains applicable in the proposed landscape has yet been confirmed. In this section, an explanation on why is SL applicable in the proposed context and the influence of SL under MLG and CAS will be given

E.1 Why is social learning applicable in MLG and CAS

In order to confirm whether SL is applicable in the proposed landscape, key concepts from MLG and SL were reviewed to evaluate whether SL is applicable. The governance perspective supports the conceptualization of the WASH sector's structure as discussed in the section 3.1, illustrating how RWSD is provided and environmentally maintained through different actors, sectors and administrative levels. The multi-level governance structure was formed using external control by the government as discussed previously; however, there is a process of which the government underwent to give rise to the structure. The perspective of governance suggests the organization with external control (government) sets limitations and specific orders for actors; while these conditions and orders could be set by the government alone, this is not the case in the domain of governance around a public collective issue (Boons, Teisman & Buuren, 2009) such as RWSD in general.

Self organization is omnipresent in governance (Boons, Teisman & Buuren, 2009), meaning the organization with external control is a part of the governed structure and process as another actor, and does not have complete control over the governance process and results towards collective public issues (Boons, Teisman & Buuren, 2009). Therefore, governance processes are coordinated arrangements between public and private actors around a collective public issue (Boons, Teisman & Buuren, 2009). In this perspective, SL as a self organized activity under governance can be justified.

“The literature on governance also highlights the importance of public participation in governance processes for the potential to ‘improve the quality of decision making by opening up the decision-making process and making better use of the information and creativity that is available in society, improve public understanding of the management issues at stake, make decision making more transparent, and might stimulate the different government bodies involved to coordinate their actions more in order to provide serious follow-up to the inputs received’ and potentially strengthen democratic processes where government does not have all the resources required to ‘manage an issue effectively’ “ (Casella, van Tongeren & Nikolic, 2015). According to this insight, SL processes as a series of self organized activities is suitable to address the need for public participation in governance processes by performing the described activities in chapter 2; and therefore increasing the potential to improve the quality of decision making for the WASH sector to reaching WSLs goals and maintaining GWLs. Since SL is a process method directed towards MLG and MLG belongs in the social dimension, SL was confirmed to be applicable in the newly proposed landscape. In the next section, the influence of SL in proposed landscape will be explained.

E.2 The influence of SL in MLG and CAS

The previous section addressed why SL is suitable to be applied in Uganda's WASH structure under the governance perspective; however, how changes occur in Uganda's WASH structure to improve or impair RWSD and GWLs under governance through SL activities have yet been explained. In this section, an explanation will be given on how SL would bring change in the proposed landscape.

SL was described as a method to influence decision making in the professional practice through different activities to address an issue in chapter 2, this can be seen as a part of the governance process. The governance process can be further categorized into adapting, learning and experimenting in the governance perspective to describe how changes occur in the structure. Actors individually learn about different solutions as there is a need to adapt to different problems, followed by experimentation, where actors learn about which solution is suitable, and finally applying the solution to make adaptations to the problem. SL occurs when actors in the structure are learning about different individual experiences and knowledge in groups by performing SL activities.

These self organized activities would in turn influence the governance structure, as the actor with external control is a part of the governance and SL process together with the rest of the actors in the sector. Self organization will also be influenced by the adjusted governance structure. Thus in the governance perspective, changes in the WASH sector can be seen as a product of evolution from the nested dynamics between actors and individual actors themselves. Selection, variation, and reproduction are the three traits of evolution, and these occur at the individual, group, and organizational level. Solutions for WSLs and GWLs are selected by the individual to learn about by testing, variation on the solution might be needed to be reproduced as the solution to the problem. SL processes also contains the elements of evolution, as one selects the knowledge or solutions suitable to be varied, learned, reproduced and experimented upon through multiple actors engaging in SL activities. The results of the previous two layers will induce change on the governance structure by means of external control. These changes at the organizational (or structural) level will also in turn either support or impair activities in the previous levels.

Due to the changes in the social dimension under MLG and SL for RWSD, the technical dimension will also be influenced by the activities in the social dimension. Decision makers are influenced by the SL process, leading to SL influenced decisions and actions to be taken for the technical dimension or social dimension. Actions and decisions could in turn influence the performances in the technical dimension, and the performance feedback from the technical dimension to the social dimension could serve as new knowledge in the SL process. The new knowledge could be used in iterative learning cycle through SL processes to continue improving the performance of the unified RWSD system proposed in section 3.2.

Appendix F: An explanation on how GW rationing could bring change in the context of the proposed STS and SL for this study

In section 4.1, limiting the total amount of water pumped at each WP was chosen to be the resource management method for this study and the related assumptions taken to reach the decision was discussed. This section will focus on explaining how GW rationing could in theory bring change in the proposed STS under SL.

As mentioned in chapter 3, the social and technical sub-systems in STS interact and influence each other. The decisions made in the social system about the extraction limit will influence the performance in the technical system and towards the limit within the technical system itself. Rationing controls the amount of water extracted at WPs, leading to an adjustment to performance factors such as: GW depletion rate and WSLs in the technical sub-system. WUs might require to travel further to collect enough water for their daily needs. WUs might also require to visit an unsafe source instead of an improved source for their domestic water needs, because the WP is non-functional due to the extraction limit. GW depletion rates is therefore reduced as well, because there are less direct extraction from the scarce resource.

The extraction limit is set from the actions belonging in the social sub-system, therefore the performances of the technical sub-system will be reviewed and adjustments to the extraction limit could occur. This is a reflection of social learning at the individual level within a district. Individuals learn through observational, experiential or behavioural learning. Experiential learning occurs when the actors in the field of practice turns their experience with the extraction limit influenced performance results into knowledge. Behavioural learning occurs when GW rationing indicate changes to the environment such as higher low flow river levels or other changes in the surroundings of the actors. Observational learning occurs when WUs and governmental organizations hear about the reports on the performance and other experiences. Rationing limit can be adjusted through the process of SL within the district and therefore influence GWL.

Actors within the WASH sector could learn about the extend of the extraction limit implemented and other technical performances from other districts through the SL process. Through SL activities, actors learn through observing knowledge presented by other districts. Rationing limits can be adjusted after reflecting and interpreting what was learned from the SL activities within their own respective district. Again, GWL could be influenced from performing SL activities revolving around the topic of rationing limits.

Appendix G: Why ABM was chosen as the simulation method for this study

As mentioned in chapter 1, real life study is not possible for this study and therefore simulation is needed. Besides synchronizing the work done by Knipschild (2016) with this study, ABM contains other functional advantages over other simulation techniques. In this section, ABM is compared to two other simulation techniques for CAS and its advantages are explained.

Agent based modelling (ABM) is one of the tools which was designed for simulating the dynamics and emergent properties of complex adaptive systems and experimentation with alternative scenarios (Casella, van Tongeren & Nikolic, 2015). The other methods for simulating complex systems are system dynamics simulation (SDS) and serious games simulation (SGS). SGS is not suitable for this study because it requires the actors in Uganda to participate in a gaming session with different scenarios, and access to these actors is unavailable. SDS models a system from a top-down perspective, by breaking the system into major components and modelling the interactions between these components (Macal, 2010). "SDS uses stocks, flows and feedback loops as concepts to study the behaviour of complex systems. The models in SDS consist of a set of differential equations that are solved for a certain time interval" (Figueredo, Aickelin & Siebers, 2011). The system behaviour is determined by the feedback effects between aggregated system components in SDS (Macal, 2010).

ABM models a system from a bottom-up perspective, individual entities and the interactions between these entities are modelled and the system is composed of these individual entities (Macal, 2010). "Agents have behaviours, which are often described by simple rules. Agents interact with and influence each other, learn from their experiences, and adapt their behaviours so they are better suited to their environment. By modelling agents individually, the full effects of the diversity that exists among agents with respect to their attributes and behaviours can be observed as they give rise to the dynamic behaviour of the system as a whole" (Macal, 2010). "Agent based models are constructed to discover possible emergent properties from a bottom-up perspective. They attempt to replicate, in silico, certain concepts, actions, relations or mechanisms that are proposed to exist in the real-world in order to see what happens" (Casella, van Tongeren & Nikolic, 2015).

ABM was chosen for this study because it could provide an environment similar to how SL is carried out in the real world; without omitting and aggregating the process of executing the SL activities in the simulation. Heterogeneity characteristics between the same type of agents are permitted in the ABM environment compared to SDS. This is useful in simulating Uganda's RWSD system, because there are multiple districts and regions each containing the same types of agents with different interests, geographical conditions, and learning abilities. Instead of aggregating these characteristics for agents of the same type in SDS, agents in ABM could interact, learn, and act based on their distinctive characteristics. Diversity of the SL group matters as stated in chapter 2, the modelling environment in ABM captures diversity in both the sub-system level (social, technical, environmental) and individual level; where SDS could only provide diversity in the sub-system level. New knowledge could be constructed during the SL process as mentioned in chapter 2, which in turn could lead to changes to the system's structure. As the system's structure is fixed in the SDS environment, ABM is suitable to

include this feature; because the system's structure under ABM environment is evolvable and non-fixed (Figueredo, Aickelin & Siebers, 2011).

Appendix H: Full list of model assumptions

All of the assumptions taken for this study and the designed model is listed below along with a short explanation on why the assumption was taken.

Assumption 1: GW recharge in Uganda was assumed to equal the low flow river stream in Uganda and therefore excluded in this study and model. This assumption was made in correspondence to the explanations in chapter 1.

Assumption 2: Climate change effects were excluded in this study and assumed to be negligible due to uncertainties. Again, this assumption was made in correspondence to the explanations in chapter 1.

Assumption 3: Actors in the WASH sector were assumed to prefer limiting the total amount of water pumped at each WP as a GW resource management strategy to implement. This assumption was made in correspondence to the explanations in chapter 4.

Assumption 4: Exact population, district area, number of WPs and location of WPs in Uganda were excluded in the model due to time constraint of the study and the information available to the author.

Assumption 5: The modelled system assumed twelve districts in the system. Each district was assumed to begin every simulation with ten WUs and five WPs, of which two of the WPs are unsafe type WPs. This assumption was made because of assumption 4.

Assumption 6: Districts were assumed to have the same surface area in the model. This assumption was made because of assumption 4.

Assumption 7: The maximum WU in a district was assumed to be one hundred and ten. This assumption was made because of assumption 4; and in correspondence to assumption 10, because a negative value in GW levels would indicate WUs are withdrawing more than the storage which does not happen in reality.

Assumption 8: Geographical characteristics were excluded due to the lack of expertise and knowledge on the hydro-geology of Uganda.

Assumption 9: GW resources were assumed to be disconnected per district in Uganda and treated as separate water tanks in the model. This assumption was made because of assumption 8.

Assumption 10: GW resources in Uganda were assumed to be completely depleted in twenty years and starting amount of GW in each district is calculated by 20 Litres per day multiplied by 7300 days over 20 years times 110 WUs. This assumption was made because of assumption 9.

Assumption 11: WUs were assumed to be able to travel freely in the district without any geographical or other constraints because of assumption 8.

Assumption 12: Assumptions were made for WU behaviour, where WUs will always visit the next closest source to finish their task of water collection. However, WUs will always visit the closest safe type WP first at the beginning of their water collection sequence. The assumption was made because there is an insufficient amount of information on WU behaviour in the rural areas of Uganda based on the author's knowledge, and real life experimentation was not possible.

Assumption 13: WUs were assumed to be able to know all of the locations and types of the WPs in their district because of assumption 12.

Assumption 14: A random percentage of the water collected from the unsafe sources will be contributed to the subtraction of WaterAmount to represent unsafe sources which are GW based due to the insufficient information sources on unsafe water sources and the hydro-geology in Uganda at the time of this study. This assumption was made after consulting the third supervisor of this study for confirmation.

Assumption 15: The effects of the national conditional grant policy on the RWSD infrastructure was assumed to be effectively taken place and phasing out unsafe sources. In addition, all of the districts in the model do receive the conditional grant annually and the grant amount is sufficient for any amount of WP increase and repairs for the next 20 years. This assumption was made because the availability and the amount of the grant differs between districts (Knipschild, 2016) and outside of the scope of this study to include the dynamics between RWSD financing, WP functionality and WP placements.

Assumption 16: The model was designed to increase only improved source type WP if a WP increase does occur in a district and placed randomly within each district. This is because it was an assumption made based on the fact where the government of Uganda is promoting safe type WPs expansion at the time of the study, mentioned in chapter 1 and chapter 4 of this thesis; as well as assuming Knipschild's recommendations on the conditional grant is in place and yielding a positive effect on the amount of functional WP overtime. An accurate representation of WP placement behaviour design falls outside of the scope of the study.

Assumption 17: All of the WPs in the model were assumed to be functioning all the time and maintenance technicians are able to acquire the suitable parts for repairing malfunctioned WPs during hours of zero demand. This assumption was made in accordance to assumption 15.

Assumption 18: GW rationing at WP was assumed to occur as follows in the model. Each DLA will apply their ration ratio based on the expected amount of GW extraction from WUs living within a return distance of 1.5km between its starting point and the safe type WP. Each WU living within a return distance of 1.5km will increase the expected amount by 20 Litres per day and the ration ratio is a percentage of the expected amount. This assumption was made because rationing as a GW resource management strategy was not applied in Uganda's RWSD system at the time of the study in reality.

Assumption 19: If no WU is expected to visit the particular WP, the expected amount was

assumed to be set at one WU's worth of water. This assumption was made in accordance to and for the same reasons as assumption 18.

Assumption 20: Technical limit of a WP was assumed to be 10 Litres by 60 minutes by 8 hours by 365 days (Whitehead, 2001), and only hand-pumps at shallow wells were considered in this study. This assumption was made because this project is based on the previous work done by Knipschild (2016) and the same assumption was made.

Assumption 21: Decisions performed by the agents was assumed to be always made under classical decision theory in this study. This assumption was made in accordance to the explanations on social learning in chapter 2 of this thesis.

Assumption 22: Knipschild's (2016) way of modelling learning (Selection, meme, replication and variation) was assumed to be sufficient for this study due to time constraint. However, parts of the SL process are omitted when Knipschild's model of learning was compared with SL literature; therefore, additional assumptions were made to address the differences.

Assumption 23: Attention and motivation were assumed to be always positive when one is participating in SL in groups. This assumption was made because the theoretical maximum effects of SL applied towards resource management for GWL can be observed.

Assumption 24: DLAs have full information about their own WPs, WUs, GWLs and ration ratios at all times. This assumption was made because the theoretical maximum effects of SL applied towards resource management for GWL can be observed.

Assumption 25: DLAs were assumed to have the power to control WPs in the model. This assumption corresponds with explanations on MLG in chapter 3 of this thesis.

Assumption 26: DLAs in a structured environment will always apply what they've learned (ration ratio from the first ranked district) if they are in the bottom half of the ranking list. This assumption was made because the purpose of the study was set to be exploring a GW resource management strategy for Uganda and decision makers were assumed to be under a scenario where the GWL have reached a critical point for action.

Assumption 27: Districts belonging in the bottom half of the learning list but containing the same GW levels will never apply and learn ration ratios from the best ranking district. This assumption was made in correspondence to assumption 21.

Assumption 28: The entire learning network and frame has been set up and connected for all districts in the model and does not change over time. This assumption was made to reduce the complexity of the model due to time constraint of the study.

Assumption 29: Each learning actor trust each other completely, therefore relational activities are excluded in the model. This assumption was made to reduce the complexity of the model due to time constraint of the study.

Assumption 30: New forms of knowledge are not created within SL activities; and are born only after the SL activities, through the SL process variation and sharing of the knowledge. This assumption was made because knowledge could be generated at the SL session where all the participating actors agree on the new knowledge being the best ration ratio to be learned and applied. Since these instances occur at random and there are no set procedures or equation to generate the best universal solution at every definitive GWL for participants during SL, this assumption was made to reduce complexity due to time constraint.

Assumption 31: Only management competence related informal-cognitive components (ration ratio) are learned in the SL process in the context of this study and only in terms of single loop learning. This assumption was made in accordance to the literature review in chapter 2 of this thesis

Assumption 32: A tick in the designed ABM represents a year in real time and the maximum model duration was set to twenty ticks. This assumption was made because ABM operates in discrete time as explained in the previous section and the model duration was set based on Knipschild's (2016) model.

Assumption 33: The designed model does not contain all factors of WSL. Water quantity was designed into the model and the water quality was designed to be represented by the types of WP agent. Exact water quality and crowding at the WP was excluded due to insufficient information available to the author at the time of study. According to assumption 4, access to WP was estimated and assumed for the designed model.

Assumption 34: WUs were assumed to be not migrating for the next twenty years due to unpredictable macro population immigration and migration patterns in the rural areas of Uganda.

Assumption 35: The population of WUs in the rural areas of Uganda was assumed to be increasing in the next twenty years due to unpredictable population patterns in the rural areas of Uganda.

Assumption 36: In correspondence to assumption 23 and 26, GWL were assumed to be at a critical level where DLA agents have to act upon it.

Assumption 37: DLA agents were assumed to learn and apply ration ratios based on GWL performance only and it is of the highest priority for DLA agents as a result of assumption 36.

Assumption 38: Assuming the sources used for this study and the design of the model to be accurate enough to be used in order to avoid the discussion of which sources are more accurate due to time constraint.

Assumption 39: Actions and activities are assumed to be operating in parallel in ABM

Appendix I: Model Narrative

I.1 ABM setup procedures:

Overview of setup:

The initialization of the model will be executing the above mentioned functions in the following order:

Clear memory

Setup breeds: WU, WP, GWL, DLA, District as mentioned in chapter 5

Setup each breed's variables as mentioned in chapter 5

Set-up Global variables:

Set-up Districts:

Set-up DLA:

Set-up GWL:

Set-up WP:

Set-up WU:

UpdateLitresExpected

UpdateLitresAllowedWithRatio

Set-up Global variables: These are designed experimentation parameters set per simulation run, variables used as metrics for the experimentation, or other variables that are used to globally in the model. These variables include:

PopulationGrowthRate: a slider value which controls how many WU will be added per district at the end of each tick

WPGrowthRate: a slider value which controls how many WP will be added per district at the end of each tick

ModelDuration: a slider value which controls how many ticks will the simulation run

NumberOfPopulationPerDistrictToStart: a slider value which controls the number of WU each district will start in the simulation

NumberOfWPPERDistrictToStart: a slider value which controls the number of WP each district will start in the simulation

NumberOfDistrictsToStart: a slider value which controls the number of districts in the simulation

SLStyle: contains a drop down menu selection of settings to be applied to the model: FR, myopic, random, or none SL

Year: contains the value of the current tick of the simulation which represents the number of years the model has simulated

ReportingSheet: contains a list of information to be exported as the simulation data

Set-up Districts: Exact district surface area, population and WPs in Uganda are excluded in the model, as it is outside of the scope of the study to predict exactly what happens to GWLs and WSL based on the flow of GWL information. Therefore, 12 district type agents are created with a same amount of surface area and population in the model. The maximum WUs population each district could hold is 110, and each district start with a population of 10 WUs

and 5 WPs. Each district will contain a space within the grid of the model and each district's territory is visualized by a square. The x and y values of the box's four corners are stored into a list type variable in their respective district agent. The district ID is stored into global list named Districts and the agent is moved to the left center edge of the district space. There is a counter created at this step, where the district is assigned to a region based on the counter. There are 3 regions, each with 4 districts within them.

Random starting surface area and population were excluded here due to the way DLAs were designed to evaluate and make decisions based on what they've learned in the model. The GWLS of a district containing less population than the other, would have a higher chance of having a higher GWL, resulting in a higher ranking position during the selection phase for the DLA. This would reduce the possibility of a DLA agent learning a ration ratio which is non-beneficial because the particular ratio is considered at a higher position than the other due to a smaller population size using less GW.

Set-up DLA: For each district, a DLA agent is created and inserted. There is one DLA agent in each district and assigned to the top-left of the district's box with a corresponding icon. The corresponding district's top edge x and y values will be retrieved before assigning the location of the DLA agent. A random ration ratio is assigned to each DLA agent. This ratio is a value between 0.01 to 1.00, and it will be re-rolled if it is 0.00. Each DLA agent will create a list of DLAs for itself, and the list contain: DLA ID, ratio, GWL, rank, and region. There is a counter created at this step, where the DLA is assigned to a region based on the counter. There are 3 regions, each with 4 districts within them.

Set-up GWL: One GWL agent is created in each district with a corresponding icon and assigned to the bottom-left of the district's box in the model. The corresponding district's bottom edge x and y values will be retrieved before assigning the location of the GWL agent. Each GWL agent is created with a set amount of water to begin with, and the amount is 20L x 365 days x 20 years x 50 WUs. Each GWL agent will create a list where it keeps track of its GWLs every year. Each GWL agent will be assigned to a district and store the ID of the district it belongs in.

Set-up WP: For each district agent, the space of which WP are allowed to spawn will be stored, then three improved type WP source and two unsafe type WP source will be added. The amount of WP for each type to be added is based on the global variable of NumberOfWPPERDistrictToStart, where the number of improve type WP added is half of the NumberOfWPPERDistrictToStart rounded up and the number of unsafe type WP added is half of the NumberOfWPPERDistrictToStart rounded down. Each WP will be given a random location within the district to operate, the corresponding symbol, and stores the corresponding ID of the district. The district will store the ID of the WP as well.

Set-up WU: For each district agent, the space of which WU are allowed to spawn will be stored, then the amount of WU based on the global variable of NumberOfWUPERDustrictToStart will be added. Each WU will be given a random location within the district to operate, the corresponding symbol, and stores the corresponding ID of the district. The district will store the ID of the WU as well.

UpdateLitresExpected: This function asks all safe type WPs to go to each WU agents in

their district and ask if the particular WU's if they would be visiting the WP in questioning as their first choice of safer water collection point. The WP agent calculates how many WU will be visiting as their first choice, and based on the distance between the WU and WP, the WP will calculate how much litres of water the WP agent is expected for withdrawal by the WU. If the distance between the WU and WP is less than 1.50 km (calculated based on a return trip distance), 20 litres will be added to the expectation; if the distance is more than 1.50km, 10 litres will be added.

UpdateLitresAllowedWithRatio: This function asks all safe type WPs to apply the ration ratio from the DLA agent in their district by multiplying the total expected amount of water withdraw at the WP with the ration ratio.

I.2 ABM Go procedures:

After the ABM is set up according to the designed experimentation parameters with agents and global variables, the following procedures are executed and repeated by the model until the terminate condition is met.

ABM go procedures overview:

Simulation termination check step:

WU water collection step

GWL update step

UpdateReportingSheet

DLA social learning step

DLA decision step

WU-Variable clear step

Population increase step

WP increase step

DLA ration ratio application step

Simulation termination check step: The global variable Year will be increased by 1 and checked against the value from global variable ModelDuration, if the difference between the two is zero, the simulation terminates and represents the preset ModelDuration amount of years have past in the model.

DLA social learning step: DLA shares their GWL between districts based on SLStyle type in this step. A separate temporary list is created and all DLA and GWL type agents will store their DLA ID, DLADistrictBelongTo, RationRatio and GWL as an item in the list. The list is created by first asking all DLA agents to add their information in the temporary list first, then ask each GWL agent to check whether the DLADistrictBelongTo value matches with GWLDistrictBelongTo. The GWL agent will store its GWL information in the respective DLA agent item slot accordingly.

If the SLStyle type is FR, the temporary list will be sorted based on GWLs with the highest value on the top of the list. All DLA breed agents will copy the temporary list into their own DLA list afterwards. The DLA agent will rank each item on the list based on their respective

GWLs.

If the SLStyle type is myopic, ask DLA agents to only copy the items on the temporary list to its own DLAList, when the region value matches with the DLA agent's DLARegionBelongTo stored value. The DLAList will be sorted again based on highest GWL value. The DLA agent will rank each item on the list based on their respective GWLs.

If the SLStyle type is random, each DLA agent will first roll a number between 0 and 12 to determine how many random items will it copy, then roll again for which item on the temporary list it will copy. The DLA agent will copy those items from the temporary list into their own DLAList and sort them based on GWLs, with the highest value being at the top of the list. There is a chance where the DLA agent will copy the same information twice, therefore it will also check its own list and remove any redundant entries. The DLA agent will rank each item on the list based on their respective GWLs.

DLA decision step: Each DLA will first locate themselves in the DLAList and the rank they are placed in their own list. Next, the DLA agent will store the best ranking ratio on the DLAList in preparation for learning. If the DLA agent is ranked lower than 50% on the list, the DLA agent will decide to act on it. The DLA agent will copy the ration ratio from the district ranking first on the list. A random dice roll between 0.0 to 1.0 determines (condition for variation is > 0.5) if the copied ratio will be slightly adjusted for variation. If the dice roll fails to meeting the preset condition, the DLA agent will replace its own ration ratio with the copied ratio right away. If the dice roll results in a number of which the preset condition could be met, another dice roll will determine whether the copied ratio will increase or decrease in comparison to the ratio it wants to copy. The amount it will adjust is a random number between 0 and the difference between the desired ratio and the original ratio. After the adjustments, the copied ratio will replace the DLA agent's starting ratio for this step. Learning of the ratio will not take place if the DLA agent's rank is placed within the top 50% of the list, at exactly 50%, or when the list only contain its own ratio.

DLA ration ratio application step: DLA applies the ratio to all safe WPs in their district. Each safe WP will recalculate how much litres it is allowed to serve by executing the UpdateLitresExpected and the UpdateLitresAllowedWithRatio functions. The explanations of these functions can be found in the set-up section of the model narrative.

ALLWU-UpdateWPList: This function updates all of the WU's unsafe type WP list and improved WP type list. Each item on these lists contain the IDs of the WPs in their district in their respective type and the distance between the WU and WP in one-way trip manner

CheckLitresDesired step: This is a function where the WU's desired litres are set based on the sum of the distance they have travelled, the travelling distance between the WU's current position and the intended WP the WU is travelling to, and from the WP back to the WU's original starting position. If the total distance is less than 1.50km, the WU will desire to collect 20L; otherwise the WU will be set to desire collecting 10L.

WU water collection step: Each WU will create a separate temporary list where they'll combine their safe and unsafe WP lists together, with all of the safe WPs first on the list

before continue adding the unsafe WPs in the list. The temporary list will not be sorted again based on distance. The list contain the ID of WPs, Location of WP, the distance between the WP and the WU's current position.

A counter variable named LitresCollected is created to keep track of how many litres of water the WU agent has collected, as well as a condition variable named LitresDesired to represent how many litres of water does the WU agent wants to collect from the WPs. A temporary variable is created to store the current position of the WU and will be set to the WU's original position here. While the value set inside of LitresCollected is not bigger or equal to LitresDesired, the WU agent will keep executing the following instructions until the condition is met.

The WU will first update the variable LitresDesired using the CheckLitresDesired function; if LitresCollected is equal or greater than LitresDesired, the WU will stop collecting water and breaks out of this function. If LitresDesired less than ListresCollected, it will check the first item on the temporary list for the WP's, then check what WP type is the WP agent.

If the WP is a safe type, the WU agent will check if the WP agent could serve water. If the WP cannot serve anymore water, the WUs will add the distance it travelled from its current position to the WP to its CumulativeTravelledDistance variable counter. The temporary position variable is updated to the position of the WP and the distance between the current position of the WU and all of the WPs in the temporary list is updated. It is because the WP of which the WU is visiting is always the first item on the temporary WP list, the first item will be removed. The list is sorted based on the distance between the WU's current position and other WPs in the district in a descending order regardless of the type of WP afterwards.

If the WP could serve more water, the WU will check if the WP can sufficiently supply the desired amount of water to be collected. If the WP could sufficiently supply the amount of water the WU is requesting to collect, the WP will replace its LitersAllowed variable value with the difference between LitresAllowed and LitersDesired. The temporary position variable is updated to the position of the WP. The value stored inside LitresDesired will be added to both the WU's TotalSafeWaterCollected and SafeWaterCollected variable. LitresCollected will be updated to the sum of the amount it originally had with the difference between LitresDesired and LitresCollected as well in order for the WU to break out of the function. The WUs will also add the distance it travelled from its current position to the WP to its CumulativeTravelledDistance variable counter.

If the WP could serve water but does not have enough water quota left to satisfy the amount of litres the WU is seeking for, LitresCollected will add the remainder litres of water the WP agent has to to itself, and change the status of the WP agent from serving to closed for the this simulation tick by changing the variable LitresAllowed to zero. The temporary position variable is updated to the position of the WP and the distance between the current position of the WU and all of the WPs in the temporary list is updated. The WU will update its TotalSafeWaterCollected and SafeWaterCollected variable by adding LitresAllowed to both variables. The first item on the temporary list is removed and the list is sorted based on distance regardless of WP type. The WUs will add the distance it travelled from its current position to the WP to its CumulativeTravelledDistance variable counter.

If the WP is an unsafe type, the distance travelled by the WU will be added to WU's CumulativeTravelledDistance variable update its current position. The amount of LitresDesired is collected and the variable LitresCollected, UnsafeCollected and TotalUnsafeCollected variable are updated.

After breaking out of the loop and before breaking out of the function, the returning distance between the current position and the WU's original position is added to the CumulativeTravelledDistance variable.

Population increase step: New WU agents are placed in each district according to the global variable value of PopulationGrowthRate. The value of population in the district agent will change for district type agents, as well as new WUs will be added in the model. If the number of new WU agents placed in the district is above 110, no new WUs will be added to the district.

WP increase step: New improved type WPs are created in each district during this phase. The amount of WP increase in this step depends on the global variable of WPGrowthRate. The district type agents' WPList will be updated accordingly.

GWL update step: All GWL agents will update their tank levels (WaterAmount variable) by visiting each WU agent in their own district and subtracting its WaterAmount variable value with the WU's SafeWaterCollected. A random percentage of the water collected from the unsafe sources will be contributed to the subtraction of WaterAmount to represent unsafe sources which are GW based due to the insufficient information on unsafe sources in Uganda at the time of this study.

WU-VariableClear: Each WU will clear their WPSafeList, WPUUnsafeList, SafeWaterCollected, UnsafeWaterCollected and CumulativeTravelled distance variables in preparation for the next simulation tick.

Simulation time update step: Global variable Year is updated by adding one to the variable to represent a year has past. If the global variable value ModelDuration is equal to Year, the simulation terminates.

UpdateReportingSheet: This function updates the global variable ReportingSheet. Values from Year, GWL, DLA and WU agents are translated into an item and stored into a list. Each item represents information from each district and their GW level (WaterAmount from the corresponding GWL agent), ration ratio (RationRation from the corresponding DLA agent) and the CumulativeTravelledDistance along with their water collection portfolios from all of the WUs in the district. Water collection portfolios are calculated as the amount of water collected from an improved type WP divided by the total amount of water collected regardless of water type. Due to computational time limitation, the water portfolios and cumulative travelled distance are sorted into categories for data export. The categories for water portfolios are: 0% - 9.99%, 10% - 19.99%, 20% - 29.99%, 30% - 39.99%, 40% - 49.99%, 50% - 59.99%, 60% - 69.99%, 70% - 79.99%, 80% - 89.99%, 90% - 99.99% and 100%. The categories for

cumulative travelled distance are: 0 km – 0.49 km , 0.5km – 0.99 km, 1 km – 1.49 km, 1.5 km – 1.99 km, 2.0 km – 2.49 km, 2.5 km – 2.99 km and 3km or above.

DataOutput: This function is called at the end of the simulation to report and export the global variable ReportingSheet, which is the result from the UpdateReportingSheet function.

Appendix J: Pseudo code

The pseudo code translates the model narrative from the previous section into a description of what the computer simulation program must do. The pseudo code is the last step before the simulation is created in the Netlogo environment (Knipschild, 2016)

J.1 ABM setup procedures

Set-up model variables:

- Clear-all
- Create breeds and define the variables of each breed: WP, WU, GWL, DLA
- Create global variables

Overview of setup:

Set-up Districts
Set-up DLA
Set-up GWL
Set-up WP
Set-up WU
Set-up Globals
UpdateLitresExpected
UpdateLitresAllowedWithRatio

Set-up Districts:

- Create temporary xy box points storage and a counter
- Repeat 12 times (according to the global value NumberDistrictsToStart)
 - create District agent
 - set population to 10 (if global variable NumberPopulationPerDistrictToStart is less than or equal to 0, reset this value to 1, if it is greater than 10, reset this value to 10)
 - set #ofWPs to 5 (If global variable NumberWPPERDistrictToStart is less than or equal to 0, reset this value to 2)
 - Give a shape symbol to the agent and colour
 - set x1-4 and y1-4 from the temporary xy box points storage on the map (box)
 - district agent stores x1-4, y1-4 in the GridList
 - set District ID into Districts global list
 - if counter is ≤ 3
 - set DistrictRegionBelongTo 1
 - if counter is ≤ 7
 - set DistrictRegionBelongTo 2
 - if counter is ≤ 11
 - set DistrictRegionBelongTo 3

- Update the stored temporary xy box points, if the box off the screen, y1-4 moves down to the next row, x1-4 resets to the starting point. If the box is still on screen, move x1-4 across
- Counter plus 1
- End repeat

Set-up DLA:

- For each district agent, repeat the following:
 - create DLA agent
 - set colour and shape
 - set location of the DLA agent to the top left of the district's box space
 - set RationRatio to a random float number between 0 to 1
 - set DLARegion and DLADistrict belong to according to the district agent's corresponding variable value
- End repeat

Set-up GWL:

- For each district agent, repeat the following:
 - create GWL agent
 - set colour and shape
 - set location of the GWL agent to the bottom left of the district's box space
 - GWLDistrict belong to according to the district agent's corresponding variable value
 - set WaterAmount to 110 x 20 x 365 x 20
- End repeat

Set-up WP:

- For each district agent, repeat the following:
 - store the district's grid box xy
 - create half of the rounded up global value NumberOfWPPERDistrictToStart amount of improved type WP
 - create half of the rounded down global value NumberOfWPPERDistrictToStart amount of unsafe type WP
 - each created WP will:
 - set colour and shape
 - a random location within the district's box will be given
 - adds itself in the corresponding WP list in the district agent
 - set WPDsitricBelognTo according the district agent's ID

Set-up WU:

- For each district agent, repeat the following:
 - store the district's grid box xy
 - set colour and shape
 - a random location within the district's box will be given
 - adds itself in the corresponding WU list in the district agent
 - set WUDsitricBelognTo according the district agent's ID

UpdateLitresExpected

- For each district, repeat the following:
 - Go through each item on the district's WPList and if the WP is an improved type
 - go through the district's WU list and count the amount of WU agents which are 0.75km from itself from all directions (1.5km on a returning distance)
 - Set LitersExpected to the result of the count multiplied by 20 litres by 365 days

UpdateLitresAllowedWithRatio

- For each district, repeat the following:
 - create a temporary variable AllowedLitres
 - set AllowedLitres to the corresponding GWL agent's WaterAmount
 - go through the WP list of the district agent and set LitresAllowed to AllowedLitres to all improved type WP agents
 - If the WP is expecting no WU visits, LitresExpected is set to the amount for 1 WU
 - multiply the corresponding DLA agent's ration ratio to all improved type WP in the district
 - If LitresAllowed of the improved type WP exceeds the technical limit of 10 Litres by 60 minutes by 8 hours by 365 days, then set LitresAllowed to TechLimit

J.2 ABM go procedures

Go procedures overview:

Simulation termination check step:
 DLA social learning step:
 DLA decision step:
 DLA ration ratio application step:
 WU water collection step:
 Population increase step:
 WP increase step:
 WU refresh WP list step:
 GWL update step:
 Total Water collected calculation step:
 Simulation time update step:

Simulation termination check step:

- If AmountOfYears equals to ModelDuration
 - Stop the simulation

DLA social learning step:

- create a temporary list (DLA , DLADistrictBelongTo, ratio, region, GWL)
 - Ask DLA breed
 - add item in the temporary list (DLA, DLADistrictBelongTo, Ratio, region)
 - Ask GWL breed
 - if GWLDistrictBelongTo is the same as the first item on the temporary list
 - add its WaterAmount into the temporary list as the last item
- If SLStyle = FR
 - Ask DLA breed
 - ask DLA ID DLA to Copy the temporary list into their own LearningList
 - Sort list based on GWLs, higher values goes on top
- If SLStyle = Myopic
 - Ask DLA breed
 - only copy the items in the temporary list when the region value in the temporary list is the same as its own DLAregionBelongTo value into the DLA's own LearningList
 - sort list based on GWL, higher values goes on top
- if SLStyle = Random
 - Ask DLA breed
 - roll the number of times the agent will have random social learning instances and store the value in variable x, the range of the random number is the length of the temporary list made at the beginning of this function
 - if x is not 0
 - set a counter to 0
 - roll which item to learn on the temporary list and store it in variable y
 - Store item y in the temporary list to the DLA's LearnList
 - repeat until counter is equal to x
 - remove duplicates in the LearningList of the DLA agent

DLA decision step:

- Each DLA do the following:
 - Determine the cut-off point on the DLA's own LearningList, and it is calculated by

dividing the length of the LearningList then subtracting one from the result because the counter position of the list begins at 0.

- DLAs determine if their district is ranked in the top half or the bottom half of its own LearningList based on the cut off point
- If it is located in the top half, do nothing
- If it is in the lower half,
 - store the DLA's original ration ratio and the ratio the DLA is about to learn
 - randomly decide if a variation on the learning ratio
 - if variation does not occur, then the DLA will replace it is own ration ratio with the learning ratio
 - if variation does occur
 - the absolute difference between the original ratio and the learning ratio will be stored
 - randomly decide if it will be a positive change or negative change
 - the amount which will be changed is decided randomly between 0 and the absolute difference and stored in variable Change
 - if it is a positive change
 - set the DLA's ration ratio to the sum of the learning ratio and Change
 - if it is greater than 1, the ratio will be changed to 1
 - if it is a negative change
 - set the DLA's ration ratio to the learning ratio subtracting the change
 - if the DLA's ration ratio is less than zero, the variable Change will be adjusted to a random number between 0 and the learning ratio
 - and the DLA's ratio will be set on the difference between the learning ratio and the new value from the variable of Change

DLA ration ratio application step:

- UpdateLitresExpected ()
- UpdateLitresAllowedWithRatio()

ALLWU-UpdateWPLists:

- For all districts
 - go through each item in the district's WPList
 - if the WP is an unsafe type
 - set the name and distance of the WP into all the WUs in the district
 - if the WP is an improved type
 - set the name and distance of the WP into all the WUs in the district

CheckLitresDesired step (CumulativeTravelledDis, WPID, CurrentXY, HomeXY):

- set travelling distance variable to the distance between Current XY and the XY of WPID

- set returning distance variable to the distance between WPID XY and HomeXY
- report 20 litres multiplied by 365 days if the sum of the CumulativeTravelledDistance, travelling distance and returning distance is less than or equal to 1.5km, otherwise report 10 litres multiplied by 365 days.

WU water collection step:

- Ask WUs to do the following:
 - get and store WU ID, the current location of the WU into current xy and home xy variables
 - set LitresDesired to 10 Litres times 365 days and LitresCollected to 0
 - set WU's XY (a separate temporary variable) to the WU's own location variable values
 - create a temporary list
 - add WU's safe list inside x (WPSafeList - WP ID, Location of WP, Distance to WP from current position)
 - sort the temporary list based the distance, shortest on top
 - add WU's unsafe list inside, right after the last item on list x
- while LitresCollected is not bigger or equal to LitresDesired:
 - set LitresDesired using the results of from the CheckLitresDesired function
 - if LitresCollected < LitresDesired
 - if the WP is an improved source type
 - if LitresAllowed of the WP is 0 or less than 0
 - set CumulativeTravelledDistance of the WU to the distance between the current xy and the location of the WP
 - update current xy
 - change the distance of between the WU at its current xy and all of the WPs in the temporary list
 - remove the WP from the list (first item on the list)
 - sort the temporary list based on the distance
 - if LitresAllowed of the WP is greater than 0
 - if LitresAllowed >= LitresDesired
 - set CumulativeTravelledDistance of the WU to the distance between the current xy and the location of the WP
 - update current xy
 - set LitresCollected, SafeWaterCollected and TotalSafeWaterCollected to the sum of their own original value, LitresDesired minus LitresCollected
 - set LitresAllowed to its original value minus LitresDesired
 - if LitresAllowed < LitresDesired
 - set CumulativeTravelledDistance of the WU to the distance between the current xy and the location of the WP

- update current xy
- set LitresCollected, SafeWaterCollected and TotalSafeWaterCollected to the sum of their own original value and LitresAllowed of the WP
- set LitresAllowed to 0
- change the distance of between the WU at its current xy and all of the WPs in the temporary list
- remove the WP from the list (first item on the list)
- sort the temporary list based on the distance
- if the WP is an unsafe source
 - set CumulativeTravelledDistance of the WU to the distance between the current xy and the location of the WP
 - update current xy
 - set LitresCollected, UnsafeWaterCollected and TotalUnsafeWaterCollected to the sum of their own original value and LitresDesired minus LitresCollected
- set the WU's CumulativeTravelledDistance to its original value plus the returning distance between current xy and home xy

Population increase step:

- For each district agent, repeat the following:
 - store the district's box xy
 - Create new WU agents and the number of WUs created is based on the global variable PopulationGrowthRate which is set by the experiment design
 - set the location of the WU within the district's box xy randomly
 - set shape and colour
 - set district agent's WUList to insert the new WP's ID and increase the #population variable of the district agent

WP increase step:

- For each district agent, repeat the following:
 - store district's grid box xy
 - create new WU agents and the number of WPs created is based on the global variable WPGrowthRate which is set by the experiment design
 - set the location of the WP within the district's box xy randomly
 - set shape and colour
 - set the district agent's WPList to insert the new WP's ID

WU-VariableClear

- For each WU agent, repeat the following:
 - set WPSafeList to an empty list
 - set WPUnsafeList to an empty list

- set SafeWaterCollected to 0
- set UnsafeWaterCollected to 0
- set CumulativeTravelledDistance to 0

GWL update step:

- Ask all WU to do the following
 - store which district it belongs to, SafeWaterCollected and UnsafeCollected
 - find and ask the GWL agent in the WU's district
 - subtract WaterAmount with the WU's SafeWaterCollected
 - subtract WaterAmount with a random percentage of the WU's UnsafeWaterCollected

UpdateReportingSheet:

- Store Year and create an empty list called ItemEntry
- ask all districts to do the following:
 - store the Year, ID of the district, GWL, ration ratio as an list item in ItemEntry
 - create two other lists named PrepEntryFract and PrepEntryCDist
 - create variables according the categories
 - go through each WUs on their own WU list
 - store the WU's ID, CumulativeTravelledDistance, SafeWaterCollected and UnsafeWaterCollected
 - calculate the water portfolio of the WU agent: $(\text{SafeWaterCollected} / (\text{UnsafeWaterCollected} + \text{SafeWaterCollected}))$
 - determine which category the WU's calculated water portfolio value belongs to and set the variable to its own original value + 1
 - determine which category the WU's CumulativeTravelledDistance value belongs to and set the variable to its own original value + 1
 - Attach the categories values to the end of the ItemEntry
 - Attach ItemEntry to global variable list ReportingSheet as the last item on the list

DataOutput

- Reports global variable ReportingSheet

Simulation time update step:

- Set Year to Year + 1

Appendix K: Model verification explanation

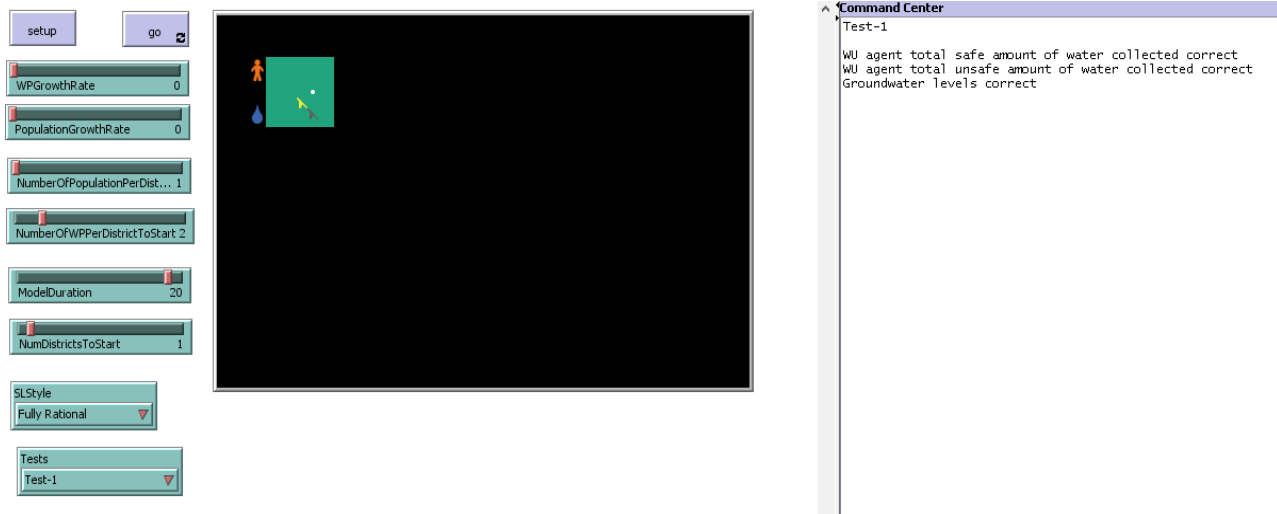


Figure 28: Verification Test1 setup and output

In the first verification test, a single agent of each WP type, GWL, WU, DLA and district was tested. The improved source type WP agent was placed in the x-coordinate of -8.5 and in the y-coordinate of 4.5; while the unsafe type WP agent was placed in the location of -8,4. The WU agent was placed in the location of -8,5, and the remainder agents were placed in their default location. Since the ration ratios are generated randomly by default, the ration ratio set for the DLA agent in this test was 1. The model environmental variables were set at 0,0,1,2,20,1,FR and Test1 in the order of WPGrowthRate, PopulationGrowthRate, NumberOfPopulationPerDistrictToStart, NumberOfWPPERDistrictToStart, ModelDuration, NumDistrictToStart, SLStyle and Tests. The aim of this test was to verify if the WU agent collects the correct amount of water from the correct WP based on a travelling distance less than 1.5km. This test also explores whether the GWL agent responded correctly from the WU agent and if ration ratios were applied correctly before social learning. The WU should first visit the improved source type WP to gather water; and since it is located within a return distance of 1.5 and the ration ratio was set to 1, the WU agent should collect 7,300 Litres of water with no water from the unsafe type WP per tick (20 Litres per day, 365 days a year). The GWL agent should contain 1,591,400 Litres of water at the end of the model simulation. There were no errors from this test as shown in Figure 28. The command centre reported the WaterAmount variable from the GW agent was correct and the total amount of improved and unsafe water collected was correct as well at the end of the simulation.

The second verification test was a copy of the first test, with the exception of the positions of the two different WP agents being switched. The focus of this test was to test the behaviour of the WU agent when the first WP the WU agent visits was indeed an improved source type WP, whether the WU agent collects the correct amount of water when the travelling distance is greater than 1.5km and if the GWL agent responds correctly. The WU agent should visit the improved type WP agent first, located further away from the unsafe type WP, and collect half as much water from the improved type WP because the total travelling distance is greater

than 1.5km. The total travelling distance between the WU and the improved type WP was 2.0km, and therefore the LitresDesired variable should only allow the WU agent to collect 10L per day.

The predicted results for the WU was 73,000 Litres of improved water over 20 ticks only and a WaterAmount of 15,987,000 Litres. There were no errors from this test as shown in Figure 29. The command centre reported the WaterAmount variable from the GW agent was correct and the total amount of improved and unsafe water collected was correct as well at the end of the simulation.

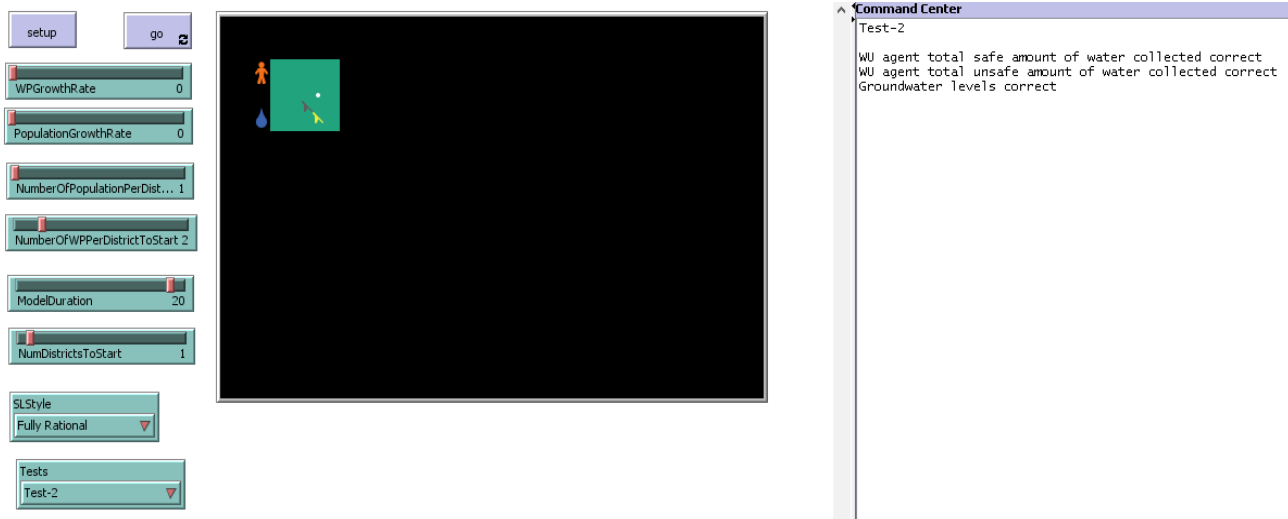


Figure 29: Verification Test2 setup and output

The third test was a copy of the first test as well, with the exception of setting the ration ratio to 0 and setting the random GW contribution percentage from an unsafe source to 0.5. By changing the ration ratio to 0, improved type WP are not allowed to serve any water and the WU agent is forced to travel to the only other WP. The WU agent's alternative water collection source in this test was set up to be an unsafe type, which means the WU agent should collect only unsafe water. Due to the distance, the WU agent should only collect 10 Litres of water per day and the GWL agent should only record half of what the WU agent collected because of the predefined GW contribution percentage. Therefore, the aim of this test was to verify whether the WU agent visits the WPs in the correct order, the ability to collect water from an unsafe type WP and whether the GWL agent respond correctly to the WU agent's actions.

The predicted results for the WU was 73,000 Litres of unsafe water over 20 ticks only and a WaterAmount of 16,023,500 Litres. There were no errors from this test as shown in Figure 30. The command centre reported the WaterAmount variable from the GW agent was correct and the total amount of improved and unsafe water collected was correct as well at the end of the simulation.

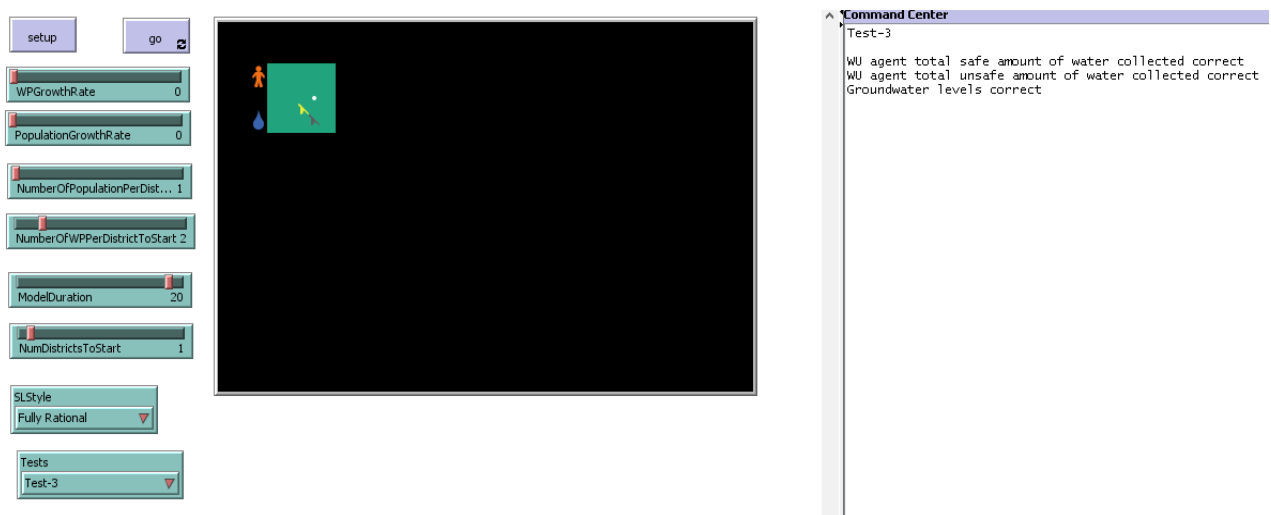


Figure 30: Verification Test3 setup and output

The fourth test was a copy of the third test, with the exception of changing the value of the WPGrowthRate model environmental variable to 1; which means a new WP is inserted into the district at the end of every tick. The new WP agents inserted at the end of every tick were set at the location of -9,6. The aim of this test was to verify whether the WU agent collects water according to the desired collection sequence when there are multiple WP agents are present in the same district; and whether WP agents are inserted at the end of every tick. Since the WP inserted at the end of every tick was set up to locate the furthest from the WU agent; and the WU agent should visit the next closest WP agent regardless of the WP type after visiting the closest improved type WP, the predicted outcome for the amount of water collected and the remaining GW amount should be the same as the third test. There were no errors from this test as shown in Figure 31. The command centre reported the WaterAmount variable from the GW agent was correct and the total amount of improved and unsafe water collected was correct as well at the end of the simulation. If the unsafe type WP agent was to be located at -9,6 and the newly inserted WP agents were to be at -8,4, the water collection results should remain the same because the collection sequence was verified.

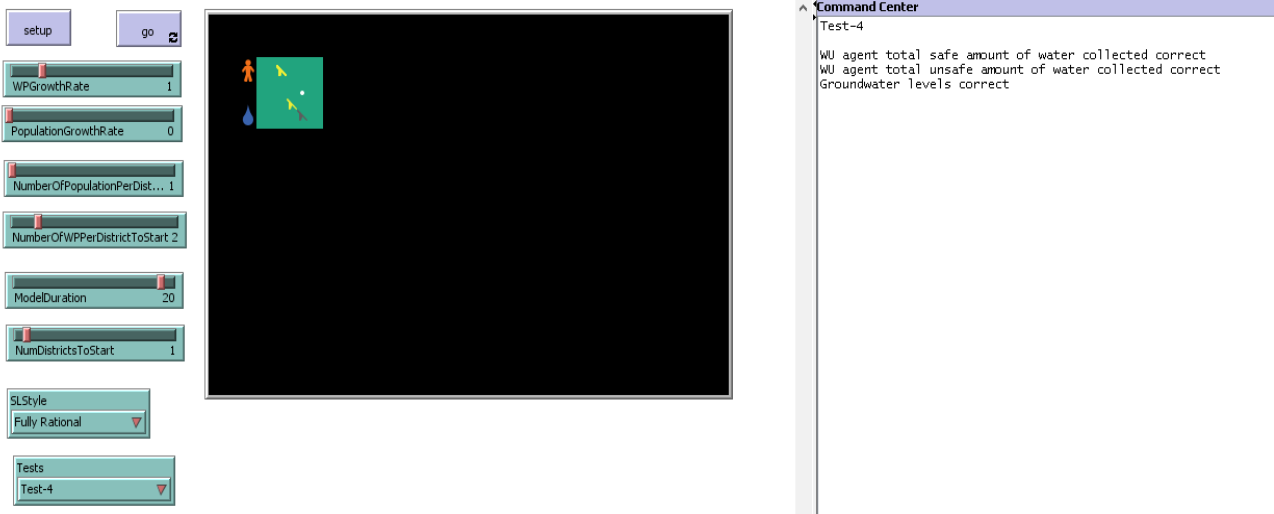


Figure 31: Verification Test4 setup and output

The fifth test was aimed to verify the model environmental conditions do not exceed the limits of the model and causing the model to malfunction. The starting conditions for this test was set at: 1,12,150,0,30,20,FR and Test5. The model can have an unlimited amount of WP; thus the WPGrowthRate variable was not tested. However, each district must start with at least one WP agent of each type otherwise WU agents cannot gather water and could cause the model to crash; therefore the starting condition for NumberOgWPPERDistrictToStart was set to 0. Due to assumption 7, the maximum number of WU in each district at the beginning of the simulation cannot exceed one hundred and ten, therefore the value for NumberOfPopultionPerDistrictToStart was set to one hundred and fifty. Again, the starting value for NumDistrictsToStart and ModelDuration due to assumption 5 and assumption 32 respectively. PopulationGrowthRate was set to a value of twelve, in order to verify if the population in each district would exceed the limit during the simulation. Figure 32 is a screen shot of the set up for this test before the setup button was pressed and Figure 33 is a screen shot of the set up after the setup button was pressed. By inspection, the slider values adjusted to the maximum and minimum settings in each model environmental variable; therefore, the model was confirmed to be able to prevent unwanted settings which would cause itself to crash before the simulation begins.

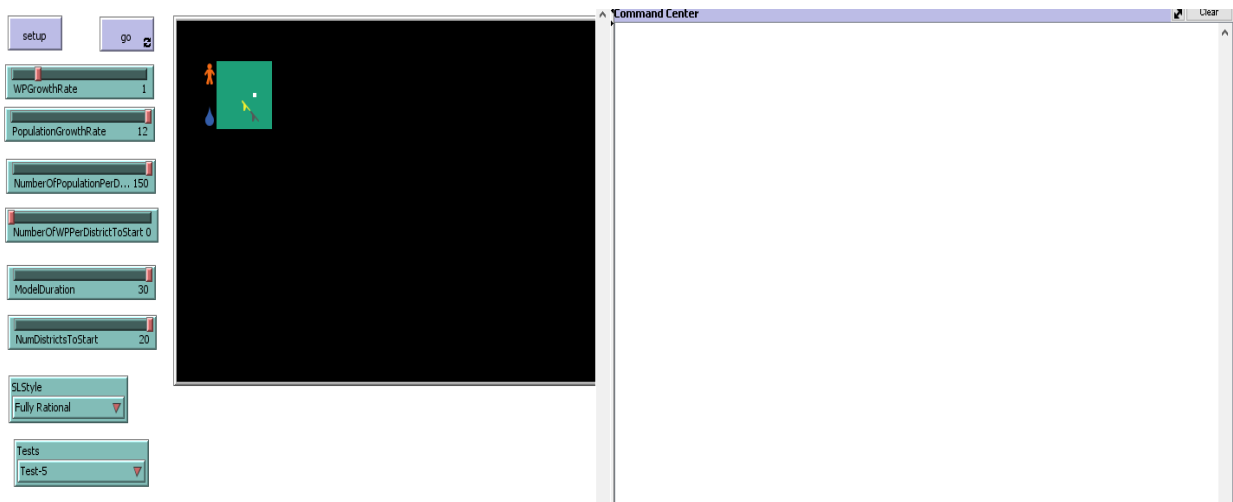


Figure 32: Verification Test5 set up, before pressing the setup button

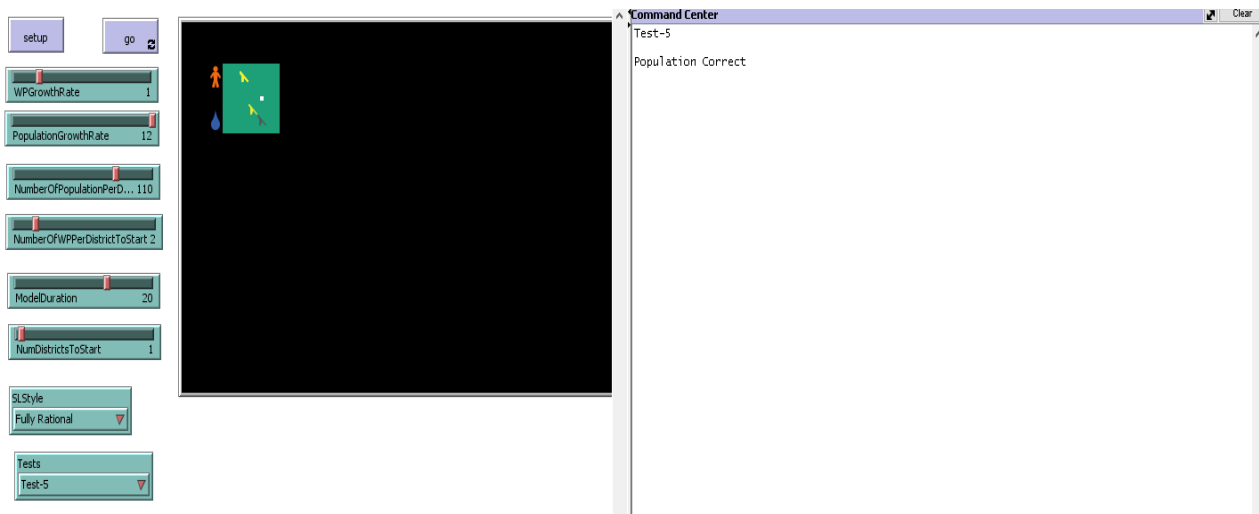


Figure 33: Verification Test5 set up, after pressing the setup button

After the setup button was pressed, the NumDistrictToStart value was adjusted to 1 and the setup button was pressed once again to continue testing whether the district limits the maximum amount of WU in the district during the simulation. Figure 34 is a screen shot of the results.

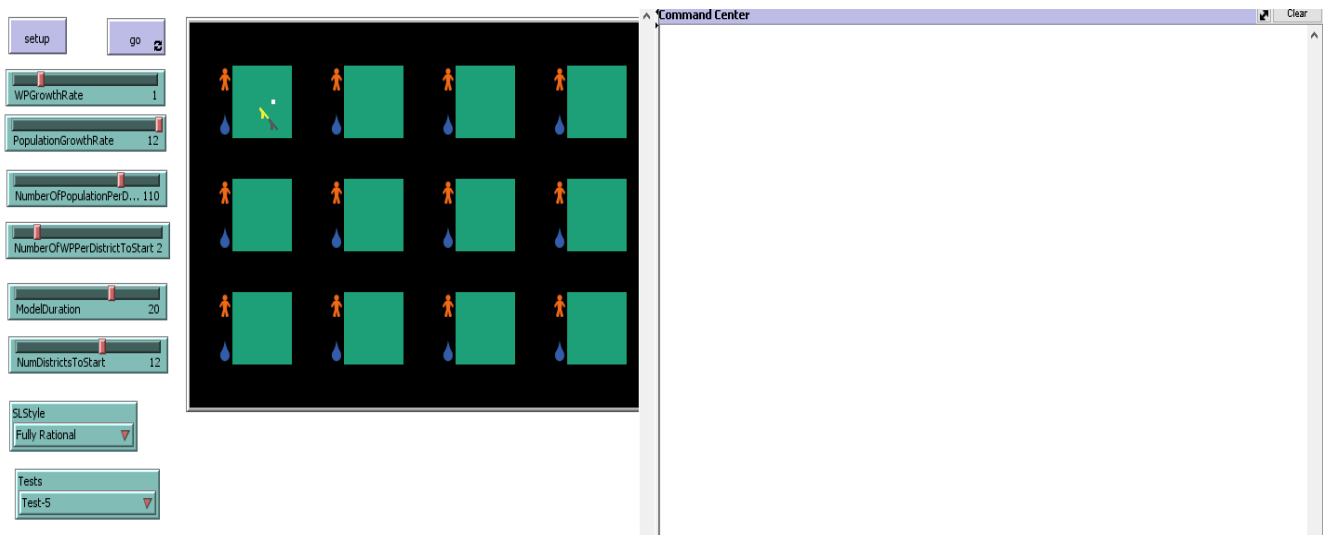


Figure 34: Verification Test5, final results

Test6 was a copy of the first test, with the exception of adjusting the NumDistrictsToStart variable to a value of four, the ration ratios for each DLA agent was not set to a value of 1 and the Tests chooser was set to Test6. The aim of this test was to verify if DLA agents learn properly under the FR SL style. In order to verify the SL process, the variation process of the SL process was turned off, each DLA received a predefined ration ratio and the ratio ratio change sequence was predicted at each tick. The predefined ration ratios were: 1, 0.75, 0.5, 0.25. The predicted ration ratio change occurrences were at the first tick for districts containing a ration ratio value of 1 and 0.75 , the fourth tick for the district containing a ration ratio of 0.5 and all DLA agents should contain a ration ratio of 0.25 until the end of the simulation from the end of the fourth tick and onward. The district containing a ration ratio of 0.5 should not learn at the third tick because of assumption 27 and if the district ranking placement is in the bottom half of the ranking list. Since the placement of the ranking list was designed to be random for the same GW level, the test was repeated until the condition of the described instance was met. The test was verified by inspection and Figure 35 is a screen shot of the command center output after the first tick. The model logs were programmed to display the DLA agent's ID and the corresponding ration ratios and learning list before and after the execution of the SL function.

```

Command Center
"Before of SL: "(dla 7)
0.75
[]
"Before of SL: "(dla 4)
1
[]
"Before of SL: "(dla 6)
0.25
[]
"Before of SL: "(dla 5)
0.5
[]

"End of SL: "(dla 4)
0.25
[[[dla 6] (district 1) 0.25 1 1.60572625E7] [[dla 5] (district 2) 0.5 1 16056350] [[dla 7] (district 0) 0.75 1 16054525] [[dla 4] (district 3) 1 1 16052700]]

"End of SL: "(dla 7)
0.25
[[[dla 6] (district 1) 0.25 1 1.60572625E7] [[dla 5] (district 2) 0.5 1 16056350] [[dla 7] (district 0) 0.75 1 16054525] [[dla 4] (district 3) 1 1 16052700]]

"End of SL: "(dla 6)
0.25
[[[dla 6] (district 1) 0.25 1 1.60572625E7] [[dla 5] (district 2) 0.5 1 16056350] [[dla 7] (district 0) 0.75 1 16054525] [[dla 4] (district 3) 1 1 16052700]]

"End of SL: "(dla 5)
0.5
[[[dla 6] (district 1) 0.25 1 1.60572625E7] [[dla 5] (district 2) 0.5 1 16056350] [[dla 7] (district 0) 0.75 1 16054525] [[dla 4] (district 3) 1 1 16052700]]

```

Figure 35: Verification Test6 after the first tick

The model logs showed the prediction was correct, where DLA 7 and DLA 4 contained a ration ratio of 1 and 0.75 respectively and the ration ratio values was changed at the end of the SL process function. This result also reflects the learning selection procedures were correct. At the third tick, the GW levels from DLA 7 which had a ration ratio of 0.75 should equal to the GW levels from DLA 5 which had a ration ratio of 0.5. Due to assumption 27, learning should not occur and Figure 36 is a the model logs at the end of the third tick and confirms learning did not take place because DLA 5's ration ratio remained the same before and after the SL process. At the fourth tick, the ration ratio for DLA 5 was adjusted to the best ration ratio which was 0.25 and the ration ratios were the same until the end of the simulation. From the model logs from Figure 37 and Figure 38 confirms the DLA agents were learning correctly, because the ration ratios were exchanged in the correct sequence and values.

```

"Before of SL: "(dla 5)
0.5
[[[dla 6] (district 1) 0.25 1 16054525] [[dla 5] (district 2) 0.5 1 16052700] [[dla 7] (district 0) 0.25 1 1.60517875E7] [[dla 4] (district 3) 0.25 1 1.60499625E7]]
"Before of SL: "(dla 6)
0.25
[[[dla 6] (district 1) 0.25 1 16054525] [[dla 5] (district 2) 0.5 1 16052700] [[dla 7] (district 0) 0.25 1 1.60517875E7] [[dla 4] (district 3) 0.25 1 1.60499625E7]]
"Before of SL: "(dla 7)
0.25
[[[dla 6] (district 1) 0.25 1 16054525] [[dla 5] (district 2) 0.5 1 16052700] [[dla 7] (district 0) 0.25 1 1.60517875E7] [[dla 4] (district 3) 0.25 1 1.60499625E7]]
"Before of SL: "(dla 4)
0.25
[[[dla 6] (district 1) 0.25 1 16054525] [[dla 5] (district 2) 0.5 1 16052700] [[dla 7] (district 0) 0.25 1 1.60517875E7] [[dla 4] (district 3) 0.25 1 1.60499625E7]]

"End of SL: "(dla 7)
0.25
[[[dla 6] (district 1) 0.25 1 1.60517875E7] [[dla 7] (district 0) 0.25 1 16049050] [[dla 5] (district 2) 0.5 1 16049050] [[dla 4] (district 3) 0.25 1 16047225]]

"End of SL: "(dla 5)
0.5
[[[dla 6] (district 1) 0.25 1 1.60517875E7] [[dla 7] (district 0) 0.25 1 16049050] [[dla 5] (district 2) 0.5 1 16049050] [[dla 4] (district 3) 0.25 1 16047225]]

"End of SL: "(dla 6)
0.25
[[[dla 6] (district 1) 0.25 1 1.60517875E7] [[dla 7] (district 0) 0.25 1 16049050] [[dla 5] (district 2) 0.5 1 16049050] [[dla 4] (district 3) 0.25 1 16047225]]

"End of SL: "(dla 4)
0.25
[[[dla 6] (district 1) 0.25 1 1.60517875E7] [[dla 7] (district 0) 0.25 1 16049050] [[dla 5] (district 2) 0.5 1 16049050] [[dla 4] (district 3) 0.25 1 16047225]]

```

Figure 36: Verification Test6 after the third tick

```

Command Center
"Before of SL: "(dla 6)
0.25
[[[dla 6] (district 1) 0.25 1 1.60517875E7] [[dla 7] (district 0) 0.25 1 16049050] [[dla 5] (district 2) 0.5 1 16049050] [[dla 4] (district 3) 0.25 1 16047225]]
"Before of SL: "(dla 7)
0.25
[[[dla 6] (district 1) 0.25 1 1.60517875E7] [[dla 7] (district 0) 0.25 1 16049050] [[dla 5] (district 2) 0.5 1 16049050] [[dla 4] (district 3) 0.25 1 16047225]]
"Before of SL: "(dla 4)
0.25
[[[dla 6] (district 1) 0.25 1 1.60517875E7] [[dla 7] (district 0) 0.25 1 16049050] [[dla 5] (district 2) 0.5 1 16049050] [[dla 4] (district 3) 0.25 1 16047225]]
"Before of SL: "(dla 5)
0.25
[[[dla 6] (district 1) 0.25 1 1.60517875E7] [[dla 7] (district 0) 0.25 1 16049050] [[dla 5] (district 2) 0.5 1 16049050] [[dla 4] (district 3) 0.25 1 16047225]]
"End of SL: "(dla 7)
0.25
[[[dla 6] (district 1) 0.25 1 16049050] [[dla 7] (district 0) 0.25 1 1.60463125E7] [[dla 5] (district 2) 0.5 1 16045400] [[dla 4] (district 3) 0.25 1 1.60444875E7]]
"End of SL: "(dla 4)
0.25
[[[dla 6] (district 1) 0.25 1 16049050] [[dla 7] (district 0) 0.25 1 1.60463125E7] [[dla 5] (district 2) 0.5 1 16045400] [[dla 4] (district 3) 0.25 1 1.60444875E7]]
"End of SL: "(dla 6)
0.25
[[[dla 6] (district 1) 0.25 1 16049050] [[dla 7] (district 0) 0.25 1 1.60463125E7] [[dla 5] (district 2) 0.5 1 16045400] [[dla 4] (district 3) 0.25 1 1.60444875E7]]
"End of SL: "(dla 5)
0.25
[[[dla 6] (district 1) 0.25 1 16049050] [[dla 7] (district 0) 0.25 1 1.60463125E7] [[dla 5] (district 2) 0.5 1 16045400] [[dla 4] (district 3) 0.25 1 1.60444875E7]]
Test-6
DLA agent RationRatio correct
DLA agent RationRatio correct
DLA agent RationRatio correct
DLA agent RationRatio correct

```

Figure 37: Verification Test6 after the fourth tick

```

Command Center
"End of SL: "(dla 5)
0.25
[[[dla 6] (district 1) 0.25 1 1.60079875E7] [[dla 7] (district 0) 0.25 1 16005250] [[dla 5] (district 2) 0.25 1 1.60043375E7] [[dla 4] (district 3) 0.25 1 16003425]]
"Before of SL: "(dla 7)
0.25
[[[dla 6] (district 1) 0.25 1 1.60079875E7] [[dla 7] (district 0) 0.25 1 16005250] [[dla 5] (district 2) 0.25 1 1.60043375E7] [[dla 4] (district 3) 0.25 1 16003425]]
"Before of SL: "(dla 4)
0.25
[[[dla 6] (district 1) 0.25 1 1.60079875E7] [[dla 7] (district 0) 0.25 1 16005250] [[dla 5] (district 2) 0.25 1 1.60043375E7] [[dla 4] (district 3) 0.25 1 16003425]]
"Before of SL: "(dla 6)
0.25
[[[dla 6] (district 1) 0.25 1 1.60079875E7] [[dla 7] (district 0) 0.25 1 16005250] [[dla 5] (district 2) 0.25 1 1.60043375E7] [[dla 4] (district 3) 0.25 1 16003425]]
"Before of SL: "(dla 5)
0.25
[[[dla 6] (district 1) 0.25 1 1.60079875E7] [[dla 7] (district 0) 0.25 1 16005250] [[dla 5] (district 2) 0.25 1 1.60043375E7] [[dla 4] (district 3) 0.25 1 16003425]]
"End of SL: "(dla 7)
0.25
[[[dla 6] (district 1) 0.25 1 16005250] [[dla 7] (district 0) 0.25 1 1.60025125E7] [[dla 5] (district 2) 0.25 1 16001600] [[dla 4] (district 3) 0.25 1 1.60006875E7]]
"End of SL: "(dla 6)
0.25
[[[dla 6] (district 1) 0.25 1 16005250] [[dla 7] (district 0) 0.25 1 1.60025125E7] [[dla 5] (district 2) 0.25 1 16001600] [[dla 4] (district 3) 0.25 1 1.60006875E7]]
"End of SL: "(dla 4)
0.25
[[[dla 6] (district 1) 0.25 1 16005250] [[dla 7] (district 0) 0.25 1 1.60025125E7] [[dla 5] (district 2) 0.25 1 16001600] [[dla 4] (district 3) 0.25 1 1.60006875E7]]
"End of SL: "(dla 5)
0.25
[[[dla 6] (district 1) 0.25 1 16005250] [[dla 7] (district 0) 0.25 1 1.60025125E7] [[dla 5] (district 2) 0.25 1 16001600] [[dla 4] (district 3) 0.25 1 1.60006875E7]]
Test-6
DLA agent RationRatio correct
DLA agent RationRatio correct
DLA agent RationRatio correct
DLA agent RationRatio correct

```

Figure 38: Verification Test6 at the end of the model duration of 20 ticks

The aim of Test7 was to verify DLA agents were learning correctly under myopic SL style. Again the ration ratios were predefined, variation of the ration ratios were turned off and the model was programmed to display the DLA agent's corresponding ID, ration ratios and learning list before and after the execution of the SL function for inspection. The minimal amount of districts required for this test was six and two districts in each of three designed regions; therefore, NumDistrictsToStart was set to a value of 6, the SLStyle chooser was set to myopic and Tests was set to Test7. The remainder sets were the same as the previous test. The predefined ration ratios were: 1, 0.88, 0.76, 0.64, 0.52, 0.4 and the predicted learning occurrences was after the first tick for DLA agents containing a ration ratio of: 1, 0.88 and 0.76. The resulting memes of ration ratios at the end of the tick should be: 0.4, 0.52 and 0.64 and there should be two of each ration ratio. From Figure 39, the model logs command centre output after the first tick confirms the prediction where DLA agent 7, 8 and 10 adjusted their ration ratios only and the logs from Figure 40 showed the DLA agents did not change

their ration ratios at the end of the simulation; and therefore, confirming DLA agents were learning correctly under myopic SL style.

```

Command Center
"Before of SL: "(d1a 11)
0.4
[]
"Before of SL: "(d1a 6)
0.64
[]
"Before of SL: "(d1a 7)
1
[]
"Before of SL: "(d1a 8)
0.76
[]
"Before of SL: "(d1a 9)
0.52
[]
"Before of SL: "(d1a 10)
0.88
[]

"End of SL: "(d1a 8)
0.64
[[[d1a 6) (district 4) 0.64 3 16055328] [(d1a 8) (district 5) 0.76 3 16054452]]

"End of SL: "(d1a 9)
0.52
[[[d1a 9) (district 1) 0.52 1 16056204] [(d1a 7) (district 0) 1 1 16052700]]

"End of SL: "(d1a 11)
0.4
[[[d1a 11) (district 2) 0.4 2 16056715] [(d1a 10) (district 3) 0.88 2 16053576]]

"End of SL: "(d1a 7)
0.52
[[[d1a 9) (district 1) 0.52 1 16056204] [(d1a 7) (district 0) 1 1 16052700]]

"End of SL: "(d1a 6)
0.64
[[[d1a 6) (district 4) 0.64 3 16055328] [(d1a 8) (district 5) 0.76 3 16054452]]

"End of SL: "(d1a 10)
0.4
[[[d1a 11) (district 2) 0.4 2 16056715] [(d1a 10) (district 3) 0.88 2 16053576]]

```

Figure 39: Verification Test7 at the end of the first tick

```

Command Center
[[[d1a 6) (district 4) 0.64 3 15971232] [(d1a 8) (district 5) 0.64 3 15970356]]
"Before of SL: "(d1a 7)
0.52
[[[d1a 9) (district 1) 0.52 1 15987876] [(d1a 7) (district 0) 0.52 1 15984372]]
"Before of SL: "(d1a 9)
0.52
[[[d1a 9) (district 1) 0.52 1 15987876] [(d1a 7) (district 0) 0.52 1 15984372]]
"Before of SL: "(d1a 8)
0.64
[[[d1a 6) (district 4) 0.64 3 15971232] [(d1a 8) (district 5) 0.64 3 15970356]]
"Before of SL: "(d1a 11)
0.4
[[[d1a 11) (district 2) 0.4 2 15997585] [(d1a 10) (district 3) 0.4 2 15994446]]
"Before of SL: "(d1a 10)
0.4
[[[d1a 11) (district 2) 0.4 2 15997585] [(d1a 10) (district 3) 0.4 2 15994446]]

"End of SL: "(d1a 6)
0.64
[[[d1a 6) (district 4) 0.64 3 15966560] [(d1a 8) (district 5) 0.64 3 15965684]]

"End of SL: "(d1a 11)
0.4
[[[d1a 11) (district 2) 0.4 2 15994300] [(d1a 10) (district 3) 0.4 2 15991161]]

"End of SL: "(d1a 9)
0.52
[[[d1a 9) (district 1) 0.52 1 15984080] [(d1a 7) (district 0) 0.52 1 15980576]]

"End of SL: "(d1a 8)
0.64
[[[d1a 6) (district 4) 0.64 3 15966560] [(d1a 8) (district 5) 0.64 3 15965684]]

"End of SL: "(d1a 10)
0.4
[[[d1a 11) (district 2) 0.4 2 15994300] [(d1a 10) (district 3) 0.4 2 15991161]]

"End of SL: "(d1a 7)
0.52
[[[d1a 9) (district 1) 0.52 1 15984080] [(d1a 7) (district 0) 0.52 1 15980576]]
Test-7
DLA agent RationRatio correct
DLA agent RationRatio correct
DLA agent RationRatio correct
DLA agent RationRatio correct
DLA agent RationRatio correct
DLA agent RationRatio correct

```

Figure 40: Verification Test7 at the end of the model duration of 20 ticks

In the eighth test, the aim was to verify if DLA agents learn correctly under random SL style. Test8 was a copy of the previous test, with the exception of the SL style chooser, Tests and NumDistrictToStart. Four districts in the model should reveal if the DLA agents were learning correctly, therefore the value of NumDistrictToStart was set to 4. The SLStyle chooser was set to random and Tests was set to Test8. Since the learning sequence was random, the only way of verifying if the DLA agents were learning correctly was to inspect the length and content of the learning list. In order to inspect DLA agents' learning behaviour under random SL style, the program was set to display the amount of learning instances and the logs of the learning instances. The learning list should not contain any duplicates and DLA agents must learn again if the ration ratio learned was itself. The length of the learning list between DLA agents should vary as well and occurrences of DLA agents not learning from any other DLA agents should be observed. Due to the length of the model log for this test, the visual evidence was selected for this report. Figure 41 shows a variety of different learning list lengths between the DLA agents after the first tick and confirms the DLA agents were learning correctly under random SL style. DLA agent 7 and 6 did not learn from any other DLA agents; while DLA agent 4 and 5 had learning instances. DLA agent 5 learned a meme of itself three times and indicated learning was repeated until a different meme was learned. DLA agent 4 had learning instances where it was learning from the same agent twice, but the duplicated meme was removed.

```

Command Center
(dla 5)
"Random instances#: "2
"Item on learninglist was: "2
[[dla 7] (district 2) 0.25 1 1.60572625E7]
"Item on learninglist was: "0
[[dla 5] (district 3) 0.75 1 16054525]
"Item on learninglist was: "0
[[dla 5] (district 3) 0.75 1 16054525]
"Item on learninglist was: "0
[[dla 5] (district 3) 0.75 1 16054525]
"Item on learninglist was: "1
[[dla 6] (district 0) 1 1 16052700]
"The DLA's LearningList was: "(dla 5)
[[[(dla 7) (district 2) 0.25 1 1.60572625E7] [(dla 5) (district 3) 0.75 1 16054525] [(dla 6) (district 0) 1 1 16052700]]]
(dla 4)
"Random instances#: "3
"Item on learninglist was: "2
[[dla 7] (district 2) 0.25 1 1.60572625E7]
"Item on learninglist was: "1
[[dla 6] (district 0) 1 1 16052700]
"Item on learninglist was: "3
[[dla 4] (district 1) 0.5 1 16056350]
"Item on learninglist was: "1
[[dla 6] (district 0) 1 1 16052700]
"The DLA's LearningList was: "(dla 4)
[[[(dla 7) (district 2) 0.25 1 1.60572625E7] [(dla 4) (district 1) 0.5 1 16056350] [(dla 6) (district 0) 1 1 16052700]]]
(dla 6)
"Random instances#: "0
"The DLA's LearningList was: "(dla 6)
[[[(dla 6) (district 0) 1 1 16052700]]]
(dla 7)
"Random instances#: "0
"The DLA's LearningList was: "(dla 7)
[[[(dla 7) (district 2) 0.25 1 1.60572625E7]]]

```

Figure 41: Verification Test8 at the end of the first tick

In the last test, variation of ration ratios were tested. Test9 was a copy of the first test with the exception of NumDistrictsToStart, Tests and ModelDuration. NumDistrictsToStart was set to 4, while Tests was set to Test9 and ModelDuration at a value of 1. The model duration was set to 1, because the model was programmed to display logs in the command centre and the output length was excessive to inspect if the ration ratio variation was functioning correctly for twenty

ticks. Since ration ratio variation occurs randomly, repetition of the test was needed until the different variation types were observed. The different variation types set to observe were: a negative variation, a positive variation and a perfect copy with no variation. Within the negative and positive variation, the special condition of exceeding the ration ratio limit of zero and one were also part of the inspection. Figure 42 confirms the normal positive variation type and the special condition of a negative variation was functioning correctly in the model. Where DLA agent 7 had a negative variation occurrence which causes the ration ratio to go below zero after the change, and it was readjusted to a random value between 0 and 0.25. DLA agent 6 had a positive variation occurrence and the resulting value matches how the variation sequence was intended to do.

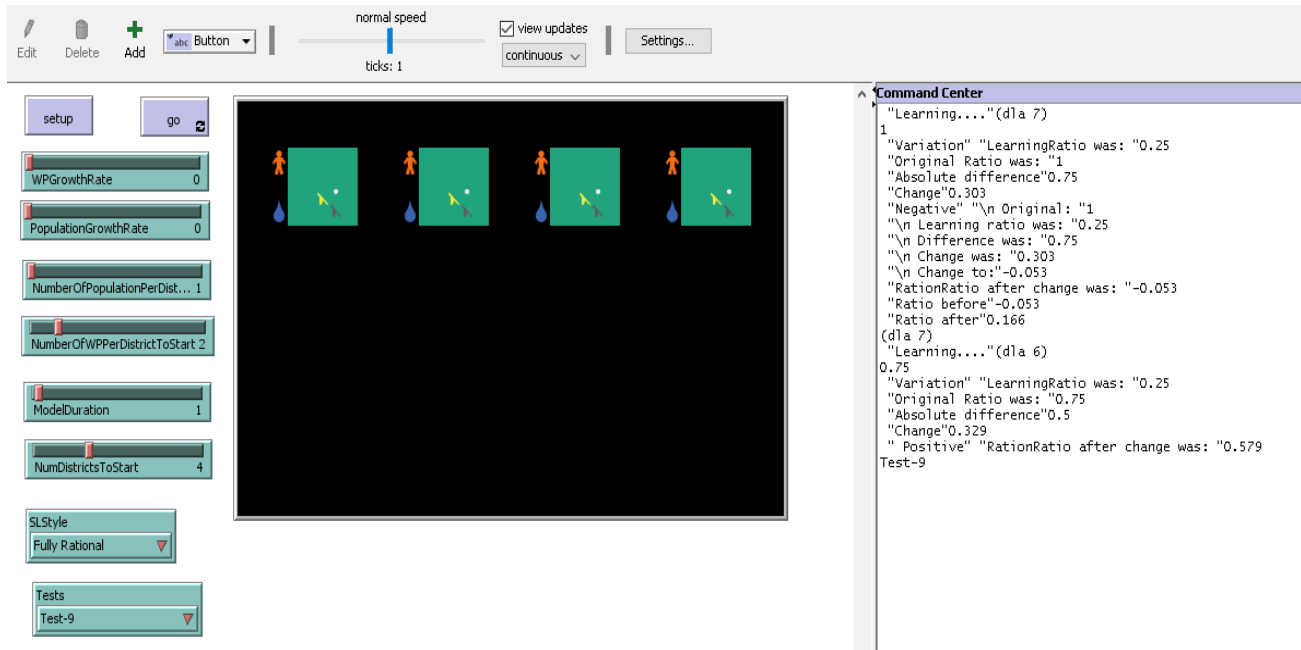


Figure 42: Verification Test9 after 1 simulation tick results version 1

Another repetition of the test confirmed the variation condition of a perfect copy. Figure 43 shows DLA agent 5 made a perfect copy of the best ranking district after the SL process and DLA agent 6 had a negative variation occurrence under normal conditions. Hence, negative variation under normal conditions and a perfect copy were confirmed to be functioning correctly in the designed model. After several repetitions, the last condition of the ration ratio exceeding a value of 1 rarely occurred; and therefore, a new section was added into the code to prompt this behaviour forcefully in a single tick by setting the change value to 2 when a positive variation occurs. Again, the test was repeated until the conditional occurred. Figure 44 was the test results for the positive variation condition exceeding a value of 1.



Figure 43: Verification Test9 after 1 simulation tick results version 2

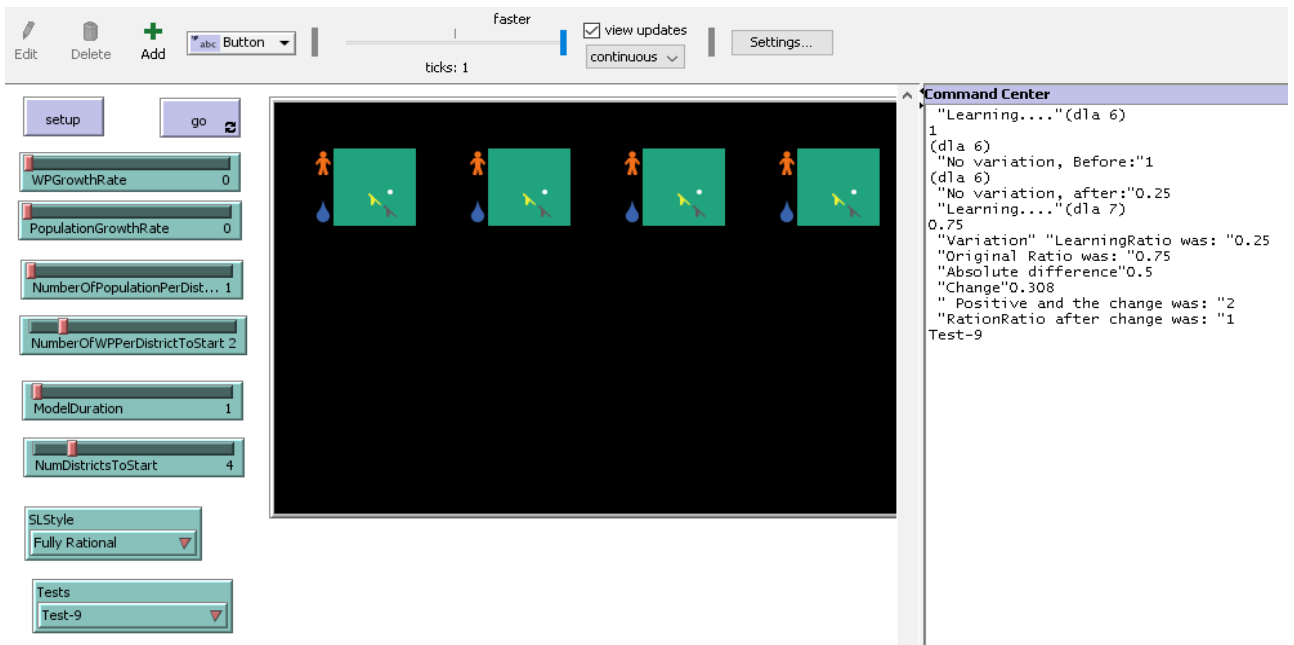


Figure 44: Verification Test9 after 1 simulation tick results version 3

DLA agent 7 from Figure 44 had a positive variation occurrence which was below a value of 1 originally. The ration ratio was changed due to the additional code made for this testing condition to a value of 2, which was exceeding the value of 1. The model adjusted the ration ratio back to a value of 1; and therefore confirming the remaining variation condition to be functioning correctly as well.

Appendix L: T-test results

The T-tests results mentioned in section 7.1 are documented in the table below:

DataSet (DS1)	DataSet (DS2)	P-value	P-value meaning	Mean values (DS1, DS2)	Findings on overall system behaviour
FR PopG1 WPG1	FR PopG1 WPG5	0.1089	Means are the same	15,502,975 15,484,210	No change of GWL as WPG increase under low steady PopG
FR PopG1 WPG1	FR PopG5 WPG1	2.2 e-16	Means are different	15,502,975 14,940,247	Change of GWL as PopG increase and low steady WPG
FR PopG1 WPG1	FR PopG5 WPG5	2.2 e-16	Means are different	15,502,975 14,544,698	Change of GWL as WPG and PopG increase
FR PopG5 WPG1	FR PopG5 WPG5	2.2 e-16	Means are different	14,940,247 14544698	Change of GWL as WPG increase and high steady PopG
Myopic PopG1 WPG1	Myopic PopG1W PG5	2.2 e-16	Means are different	15,349,813 15,038,075	Change of GWL as WPG increase and low steady PopG
Myopic PopG1 WPG1	Myopic PopG5 WPG1	2.2 e-16	Means are different	15,349,813 14,300,949	Change of GWL as PopG increase and low steady WPG
MyoPop G1WPG 1	MyopicPopG5WPG5	2.2 e-16	Means are different	15,349,813 13,925,060	Change of GWL as PopG and WPG increase
Myopic PopG5 WPG1	Myopic PopG5 WPG5	3.8 e-13	Means are different	14,300,949 13,925,060	Change of GWL as WPG increase and high steady PopG
Random PopG1 WPG1	Random PopG1W PG5	2.2 e-16	Means are different	15,532,950 15,373,559	Change of GWL as WPG increase and low steady PopG
Random PopG1 WPG1	Random PopG5 WPG1	2.2 e-16	Means are different	15,532,950 14,768,390	Change of GWL as PopG increase and low steady WPG
Random PopG1 WPG1	Random PopG5 WPG5	2.2 e-16	Means are different	15,532,950 14,456,268	Change of GWL as WPG and PopG increase

Random PopG5 WPG1	Random PopG5 WPG5	2.2 e-16	Means are different	14,768,390 14,456,268	Change of GWL as WPG increase and high steady PopG
FR PopG1 WPG1	Random PopG1 WPG1	0.00642	Means are different	15,502,975 15,532,950	Districts performed differently under FR and random
FR PopG1 WPG5	Random PopG1 WPG5	1.206 e-15	Means are different	15,484,210 15,373,559	Districts performed differently under FR and random
FR PopG5 WPG1	Random PopG5 WPG1	4.595 e-09	Means are different	14,940,247 14,768,390	Districts performed differently under FR and random
FR PopG5 WPG5	Random PopG5 WPG5	0.02803	Means are different	14,544,698 14,456,268	Districts performed differently under FR and random

Table 8: T-tests results mentioned in section 7.1

Appendix M: Domain expert consultation transcript

Meeting members: Deirdre Casella, Angela Huston, Sway Leung

Meeting date: Thursday, March 29th, 10:00am – 11:15am

Meeting place: The box, IRC office, Bezuidenhoutseweg 2, 2594 AV Den Haag, the Netherlands

The designed model, results from the performed experiment and model assumptions were presented to domain experts Angela Huston and Deirdre Casella. The expert feedback and comments on the presentation is documented. This transcript was made by the author of this thesis report and was edited by Deirdre Casella to ensure the content of the meeting was correct.

- 1) The way districts and population was modelled reflects village level in reality.
- 2) The model can be improved by adding WP placement behaviour. If there's x amount of users collecting water at a WP, another WP will be placed in a nearby proximity. Cutting off the amount of WUs are able to visit a single WP also could reflect the crowding situation at a WP in reality.
- 3) The model can be improved by adding geographical characteristics and population placement characteristics of the rural areas of Uganda. This includes macro migration behaviour of the population.
- 4) The model can be improved by adding the learning at the WU level; rationing policy can lead to lower water service level at a given WP (by causing crowding / decreased accessibility). WU chooses to go directly to an alternative WP where a greater volume of water is available for collection due to (less) crowding / increased accessibility or directly visit the unsafe type WP after learning they have to visit a certain amount of WPs overtime to obtain same volume. This is because in reality WUs do learn from experience and learn from the word of mouth.
- 5) The assumption that WU agents are always visiting improved type WP first followed by the next closest WP regardless of type is correct; however, in reality, WUs might choose directly to travel to the unsafe type WP which could lead to different results in the amount of distance travelled and the WU agents' water collection portfolio.
- 6) Beware of the terminology of the “best” meme and what is defined as the best meme; because in the WASH sector the best meme represents a meme which would yield the best WSL instead of GWL.
- 7) In the context of exploring a GW resource strategy, the decision making phase in the model makes sense. In reality, the results of WSLs and ration ratios reflect critical GWLs where decision makers must act. In extreme situations, WUs and decision makers are more likely to accept the extreme RWSD situations presented in the model results. Piped networks represent another scenario where rationing behaviour from the experiment results potentially

reflects situations in reality. Consider a piped network with a fixed volume of water supply which completely depleted. Rationing behaviour from the model is similar to reality according to the described situation, and water users could be forced to only collecting 5L per person, as the supply system is depleted.

8) Under non-critical situations, learning and applying ration ratios would not result in the way it was presented (close to 0%) and there should be a greater amount of water available for extraction . This is because different decision makers have different priorities in their own respective agendas. In other words, DLA agents stop learning and applying ration ratios at some point during the simulation according to their own agendas.

9) Collective pressure to change GW withdrawal rates was not represented in the model because the GWL are independent from one another in each district. The model can be improved by placing an additional sequence where collective pressure to change GW withdrawal rates is possible between DLA agents of each district and adjusting the GWL to be a unified unit across districts rather than as separate units. This also calls for an adjustment to the structure of the meme and how DLA decides whether or not to learn and apply ration ratios. Ration ratios and GWL should remain within the meme, and the total GW withdrawn from improved type WP in each district should be shared as well.

10) There are other factors which could lead to GW rationing and the resulting WSL effect from the model besides a top-down regulation placed in Uganda because of GW scarcity. If the price of water increases, the amount of water available for an individual at the improved type WP would also decrease due to unaffordability. Another factor could be crowding which results in individuals collecting less water at the improved type WP due to pressure for the individual to finish collecting water quickly. There could also be instances where there is no water coming out of the hand-pumps at the improved type WPs in reality due to poor maintenance / break down of the infrastructure.

11) Applying ration ratios to industries instead of WU might lead to a faster GW rationing effect. GW rationing on rural domestic users only makes sense when they are obtaining more than 20L/d; however, decision makers would not ration below basic WSL unless it is in an extreme situation.

12) Water collected from the improved type WP has other uses in the rural areas of Uganda such as: local livelihoods and economic value.

13) Although the way WU agents was modelled to behave in the simulations did not reflect the actual WU experience in reality, the results do reflect an informal form of rationing where GW rationing is not regulated from governmental authorities.

14) Building rainwater harvesting and storage to diversify Uganda's RWSD portfolio is a fair and valid recommendation in the technical domain for a GW scarce future. If GW rationing is taken place under a top-down regulated mechanism and the WSL effects under rationing are reflecting the extremes presented in the results of the simulation, a subsidy program is expected to be made by one of the actors in the MLG system, in order to help households to get rainwater harvesting and storage installations.

15) Introduction of a new practice (rainwater harvesting and storage) would require SL in rural areas of Uganda. What needs to be learned by agents about this technical practice? What do people need to do to introduce and take up such a practice? What role can policy play to stimulate this?

16) Water users would be willing to pay more for an alternative means if the alternative can save WUs from having to visit many different WPs in order to meet their water needs; even if it is not available in a centralized manner.

17) Rainwater storage could be a valid recommendation because in a similar example, WUs collect water at improved type WPs even when WUs have enough water to use on the same day and then transfer the collected volume to the rainwater storage system for future use.

18) Buying water for some parts of the population could also be a recommendation

19) Water users in the rural areas are already using the gathered water to its maximum potential and practicing many different strategies to reduce, reuse and recycle water. Therefore, further strategies that rely on these behaviour changes are not considered feasible recommendations. There is a hierarchy of water use in the rural areas of Uganda. Drinking and cooking is of the highest priority, followed by washing of the body, dishes and clothes, then feeding animals and other uses. Some WUs feed animals with their used cooking water.

20) The structure of SL was designed to be represented through nodes (districts) and the connection between districts as edges. In reality, there are information brokers in Uganda and the connection between districts might not be a direct connection as designed in the model.

Appendix N: Insights gained after the interview - model design

Since the designed model was made to represent the conceptualized STS in the ABM, the designed model is multiple steps away from the reality in Uganda and critical feedback on the way agents and objects were designed in the model was expected. The remarks from the domain experts were summarized into particular elements about the model and are briefly discussed afterwards.

GW resource management strategy of rationing WUs: Applying ration ratios to industries instead of WUs might lead to a faster GW rationing effect in reality.

This remark was logical because the extraction volume from industries are similar to domestic users as shown in Figure 1. Regulating WUs in the rural areas for rationing could require a larger amount of resources to implement compared to regulating industries. Industries can be monitored, sanctioned, and held responsible for over extraction as consumption rates can be estimated through processes and reports. Compared to WUs, it is difficult to monitor which WU extracted more volumes than the designated amount; and additional resources and organization is needed to put rationing in place for domestic WUs.

Scale of the model: The way districts and population was modelled reflects village level in reality instead of a district.

This remark was expected as it was a trade off made in the design of the model to reduce computational time due to the time constraint of the project. However, the dynamics between the decision making and learning agent (DLA), SL, WUs, WPs and GWL should remain the same in the scope of this study under the MLG perspective. This is because there are sub-county committees and water user committees at the village level of which contains certain forms of control to allow the implementation of GW rationing possible. Although the interests of the above mentioned organizations might oppose to the idea of rationing, the purpose of this study was to explore what happens when actors within Uganda's MLG system agrees to implement rationing as a GW resource management strategy.

WP placement behaviour in the model: New WP agents were placed randomly in each district every tick and does not reflect how new WPs are placed in reality.

In reality, the location of which new WP are placed does not occur randomly. Factors such as: financial ability, hydro-geological and WU crowding determines where the new WP should be placed. This remark was expected as a full design and conceptualization on WP placement behaviour was considered outside of the scope of the thesis, and therefore was addressed using assumption 16. Since cumulative travelled distance is one of the key elements of WSL, the observations made from Figure 43 is sensitive and a different insight might be observed if WP were placed in a different manner. A new WP placed closer to WU agents could lead to a higher allowance at the new WP agent. Hence, GWL could be lowered due to more WUs could get access to GW directly, WUs could collect more water from an improved source leading to better water collection portfolio and travel less to collect the required amount of water resulting in a better WSL.

District and GWL agents in the model: The absence of geographical characteristics does not reflect how WU travel in reality and the absence of hydro-geological characteristics of GWL in Uganda does not reflect how GWL responds to domestic GW demand in reality.

This remark was expected as geographical characteristics of a district can influence the travelling factor of WU and a different WSL pattern could emerge from the results of the experiment. GW recharge and other hydro-geological characteristics were excluded in the model design as well and the GWL in each district can be different compared to the experimental results from this study.

WU population behaviour in the model: The random placement of WU in each district at every tick does not reflect current and future micro and macro migration and settlement patterns of WUs in reality.

Future local and macro settlement and migration patterns in Uganda are difficult to predict with precision and beyond the scope of the project to include, therefore, the remark on the simplification of WU population behaviour in the designed model was again expected. WUs migrating from one district to another could influence the outcome of GWL in a district in the designed model and settlement patterns can lead to different final WSL results as WU agents can be placed closer or further away from WP agents. The possibility of adding or reducing family members for a WU agent were excluded in the designed model and can lead to a different GWL pattern in a district.

WU water collection behaviour : The way WU agents was modelled to behave in the simulations only partially reflect the actual WU experience in reality. The assumption of always visiting improved type WPs first followed by the next closest WP regardless of type is a correct WU water collection behaviour However, the assumed water collection behaviour does not completely reflect WU experience in reality due to the absence of learning for WU agents in the model.

GW rationing can lead to lower WSLs at a given WP (by causing crowding / decreased accessibility). In reality, WUs can choose to go directly to an alternative WP where a greater volume of water is available for collection due to (less) crowding / increased accessibility or directly visit the unsafe type WP after learning they have to visit a certain amount of WPs overtime to obtain same volume. This is because in reality WUs do learn from experience and learn from the word of mouth. According to the WU collection behaviour described by the domain experts, the influence of the change in WU collection behaviour on the overall average of water collection portfolios in the model is marginal. As shown in Figure 43, the amount of WU containing a water collection portfolio fraction of 100% unsafe water was high and there were minimal amounts of WU in between the extremes of the water collection fraction, meaning there were a large amount of WU agents visiting the unsafe source as an alternative in the simulation. The ability for WU to choose to go directly to an alternative WP where a greater volume of water is available would imply a direct visit to the unsafe type WP agents within the district and would not alter the results of the overall WSL in terms of water collection portfolios. However, directly choosing to visit the unsafe type WP agent could potentially alter the overall WSL results in terms of cumulative travelled distance.

DLA agent decision making phase: In the context of exploring a GW resource strategy, the decision making phase in the model was logical and only partially reflect reality.

The results of WSLs and ration ratios reflect critical GWLs where decision makers must act in reality. In extreme situations, WUs and decision makers are more likely to accept and act towards the extreme rationing RWSD situations presented in the model results. However, collective pressure to change GW withdrawal rates can also influence decision making on GW rationing under extreme situation. Since collective pressure to change GW withdrawal rates was not represented in the model because the GWL were designed to be independent from one another in each district; the decision making phase only reflect a portion of reality. The simplification of the decision making phase in the model was sufficient for the purposes of this study nonetheless, because the results did reflect reality under extreme situations. However, the findings from the experiment are not applicable to normal situations as the decision making behaviour could be different and lead to different findings.

SL phase: Although there were no overall remarks made about the structure of SL and how SL was designed to be carried out in the model, a remark was made about the interpretation of the SL structure in the designed model. Although DLA agents must be connected to share and learn memes in the model, DLA agents between two (or multiple) districts does not need to be directly connected to learn and share memes as there are information brokers in Uganda.

According to the remark made by the domain experts about information brokers, the influence in the model results was considered low in information brokers were added in the model. This is because from the perspective of transferring memes, the meme going through an information broker does not change the fact where the meme gets transferred from one district to another. However, the described interpretation of meme transfer only applies under the assumptions made for the designed model in this study. The absence of relational and network forming activities between agents allows meme transfer to be interpreted as described and a different pattern might emerge when the network was not assumed to be formed and steady as it was in the model. In reality, the SL network changes over time and relational activities takes place to form and stabilize the SL network. For example, if district A is not connected to district B because of trust or other factors and district A contains a useful meme for district B, the designed model would not allow SL to take place as the two districts are not connected. The inclusion of an information broker would therefore bring the designed model closer to reality when network formation and relational activities are included in the model. Lastly, SL was conceptualized using Knipschild's (2016) method and it is only one of the ways to conceptualize and model SL; therefore different results might emerge using other methods of conceptualizing and modelling SL in ABM.

Appendix O: Insights gained after the interview - findings and interpretations

During the domain expert consultation meeting, feedback on the findings and interpretations of the experiment results were discussed apart from the design of the model. In this section, the description of the validation phase continues on how did the findings and interpretations from the experiment at the point of estimated reality reflect the actual reality in Uganda.

Ration ratios approached zero over time and undesired WSLs: Under non-critical situations, learning and applying ration ratios would not result in the way it was presented (close to 0%) and there should be a greater amount of water available for extraction. This is because different decision makers have different priorities in their own respective agendas. In other words, DLA agents stop learning and applying ration ratios at some point during the simulation according to their own agendas. GW rationing on rural domestic users also only makes sense when they are obtaining more than 20L/d; however, decision makers would not ration below basic WSL unless it is in an extreme situation. However, the results do reflect reality under critical situations. This is because in extreme situations, WUs and decision makers are more likely to accept and act towards the extreme rationing RWSD situations.

Interpretation of rationing and WSLs behaviour in the model: Although the way WU agents were modelled to behave in the simulations did not reflect the actual WU experience in reality, the results do reflect an informal form of rationing where GW rationing is not regulated from governmental authorities. Piped networks represent a scenario where rationing behaviour from the experiment results potentially reflects situations in reality. Consider a piped network with a fixed volume of water supply which completely depleted. Rationing behaviour from the model is similar to reality according to the described situation, and water users could be forced to only collecting 5L per person, as the supply system is depleted instead of being forced to collect 5L per person due to rationing regulations.

There are other factors which could lead to GW rationing and the resulting WSL effect from the model besides a top-down regulation placed in Uganda because of GW scarcity. If the price of water increases, the amount of water available for an individual at the improved type WP would also decrease due to unaffordability. Another factor could be crowding which results in individuals collecting less water at the improved type WP due to pressure for the individual to finish collecting water quickly. There could also be instances where there is no water coming out of the hand-pumps at the improved type WPs in reality due to poor maintenance / break down of the infrastructure.

The difference in performance under different SL styles: Although there were no remarks made about the different performances under different SL styles and the application of network theory during the meeting, an argument was made to validate this finding using evidence from the real world.

In chapter 3, the landscape of RWSD in Uganda was described and there are different learning alliances and organizations in Uganda currently for improving WSL. Meetings and reports are made available for actors to participate and receive in a structured manner and it can be interpreted as a sign of a positive influence on WSL because these products and activities would be stopped if the influence was neutral or negative. The raise of learning

alliances and organizations can be interpreted as a sign of wanting to change the learning structure from random or myopic towards a fully rational style. On paper, learning alliances and organizations might seem exclusive to participating members and the SL style should be myopic in reality; however, there are information brokers as mentioned in previously in this chapter which can increase the connectedness and steadiness of the learning network.

Although the designed model contained simplified dynamics and did not completely reflect reality as discussed in section 8.1, the insights gained from the experiment were confirmed through the feedback gained from consulting domain experts and the findings gained from the experiment are legitimate under extreme situations in reality.

Appendix P: Author's personal suggestions on the recommendations made based on this study

Rationing policies for industries

The financial resources gained from fines, tariffs and taxes for GW rationing can be redistributed to WU in different forms such as: loans to install RWH technologies or tariff reduction to use improved sources to increase WSL. An example of a tariff and taxation policy for industries is for the national government to charge an annual fee based on the amount of GW used for producing goods and services. Another example is to increase export tax on goods which uses GW.

How to diversify the RWSD infrastructure in Uganda using RWH and how to address the current problems with RWH in Uganda

The diffusion of RWH technologies in rural areas requires SL to spread the knowledge about the technology and removing different implementation related constraints. According to the RWH technology handbook by the ministry of environment in Uganda (Kamuntu, n.d.) and literature reviews (van Tongeren, 2014), there are three main problems with the diffusion of RWH. The first problem is the political landscape, WUs in Uganda believe water should be free and the government should be held responsible for the delivery of free water. During extreme situations of GW scarcity, WUs are more likely accept the recommendation of RWH. Policy efforts can be placed in education to create awareness of GW supply related issues to relax beliefs.

The second problem is RWH designs often contain locally unavailable materials and therefore increasing the costs of implementation because the rural areas are hard to reach (Kamuntu, n.d.). The cost of most RWH designs are difficult for average rural WUs to install. Pro-poor growth policies can be implemented to address the problem of high implementation costs. In order for pro-poor growth policies to take place and to become more efficient, a pro-poor growth political landscape is needed. WASH sector actors can lobby for politicians with pro-poor priorities to change the political landscape as an example. Another example is to alter internal constraints such as beliefs, values and aspirations (Ghosal, 2013) of WUs to create a demand for pro-poor politicians. Policies for increasing the amount of scholarships, spreading of knowledge about water supply and demand and other educational needs in the rural areas are example strategies to alter internal constraints.

External constraints can also be relaxed to enable more WUs to get access to the technology. Investments in infrastructure such as roads to reduce costs of transportation. The suggestion of investing in roads was not made only for the purpose of diffusing RWH technologies, but also related to pro-poor growth. Since 75% to 80% of agricultural goods are produced from poor subsistence farmers in the rural areas (Owori, 2017), investing in the transport infrastructures can allow agriculture goods to reach national and international markets and increasing the income of rural Ugandans to afford locally unavailable materials. Another way of relaxing external constraints is to provide sponsorship, subsidies and credits to WU for installing RWH technologies; and this requires national budget allocations to favour water supply.

There are cheaper RWH options for rural WU in Uganda such as the Bob rainwater bag (Kamuntu, n.d.). Local materials are used for construction; however, it is easily vandalized or stolen (Kamuntu, n.d.). The issue of vandalism and security can be addressed through design and innovation. An example of a design improvement suggested for the improvement of the Bob rainwater bag is to raise the platform and surround the RWH bag from the outside using locally available resources such as cement and bricks. The platform and the brick fence can be attached to the side of the house and WUs can get access to the bag from within the house through the walls or existing window space of the house. Strategies such as government hosted international design competitions is an example where design improvements for cheaper RWH options can be gathered and upgrade cheaper RWH options to become more feasible for WUs to implement.