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TRANSITIONING OF URBAN WATER DISTRIBUTION SYSTEMS

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by

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DEDICATION

To my Dad who underwent an operation when I was about to complete my study and to my Wife and our children Tabitha, Tiana Nathan and Jotham whom I dearly missed

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LIST OF ACRONYMS/ABBREVIATIONS

ABM	Agent based models
AHP	Analytical Hierarchy Process
BIC	Burst Transition Impact Cost
CI	Consistence index
DFC	Design for change
DPSIR	Driver-Pressure-State-Impact-Response
I-UWDS	Iganga Urban Water Distribution System
JICA	Japanese International Cooperation Agency
KUWDS	Kampala Urban Water Distribution System
LIC	Leakage Transition Impact Cost
MADT	Multiple Attribute Decision Technique
MAVT	Multi-Attribute Value Technique
MCDA	Multi Criteria Decision Analysis
MCDAT	Multi-criteria Decision Analysis Technique
MDG	Millennium Development Goals
MCDT	Multi Criteria Decision Technique
MNL	Multinomial logistic regression
MODT	Multiple Objective Decision Technique
MOOA	Multi-objective optimisation approach
MNL	Multinomial Logistic Regression
NTS	Network Transition Score
NWSC	National Water and Sewerage Corporation
OECD	Organization for Economic Cooperation and Development
OIC	Operation and Maintenance Transition Impact Cost
OPT	Optimal Path for Transitioning
PBR	Pipe Breakage Rate
PTIC	Pipe Transition Impact Cost
RCI	Random Consistence index
RWDN	Rubaga Water Distribution Network

RWDS	Rubaga Water Distribution System
SE	Socio-economic Impact
SEIA	Social and Economic impact analysis
SIC	Socio-economic Cost
SII	Socio-economic Impact Indicator
SMART	Simple Multi-Attribute Rating Technique
ST	Social Technical Index
TCDZ	Town Central Distribution Zone
TIC	Technical Transition Impact Cost
TIS	Technology Innovation System
UBOS	Uganda bureau of statistics
UC	Urban Characteristic Impact
UDHS	Uganda Demographic and Health Survey
UI	Urban Infrastructure Impact
UNICEF	United Nations Children’s Fund
USAID	United States Development Agency
UTDO	UWDS Transition Options
UTIAM	UWDS transition impact assessment methodology
UWDS	Urban Water Distribution System
WDN	Water Distribution Network
WDS	Water Distribution System

ABSTRACT

The upgrade of urban water distribution systems (UWDS) amidst uncertain global change pressures is a challenging problem. To deal with this dilemma water utilities require approaches that enable UWDS to be changed at a minimal impact cost as the uncertainties become known. This thesis describes approaches designed for the upgrade and transition of UWDS sustainably and their application on case studies.

Presently a methodology to quantify socio-economic impacts due to UWDS upgrades is lacking. To address this issue, a novel Socio-economic Impact Indicator (SII) framework based on Multi Criteria Decision Analysis (MCDA) and the Analytical Hierarchical Process (AHP) to compute weights is developed. The approach enables decision-makers to eliminate those with high SII or high cost. Next, a novel approach to model the relationship between household socio-economic characteristics and the transition in UWDS options is developed based on multinomial logistic regression (MNL). The approach can be used by decision-makers to identify critical socio-economic characteristics to overcome barriers to UWDS transitioning.

A new approach for upgrading UWDS that introduces transition and socio-economic impact costs into conventional models that are biased towards operation and maintenance costs is developed based on the Urban Transition Impact Assessment Methodology (UTIAM). The framework is based on concepts from image morphing, product platforms and graph transition systems. UTIAM is implemented by linking EPANET2 with a genetic algorithm (GA) UWDS transition platform optimizer using the Visual C++ to create a tool that determines UWDS options with the least impact on the future. For uncertain future UWDS states, designing with the consideration of transitionability and socio-economic impacts ensures maximum cost savings as compared to the conventional approach.

The successful application of the transition design and analysis approaches on two case studies demonstrates that it is a suitable strategy for addressing challenges related to uncertain global change pressures. These approaches have the potential to enable engineers and planners make more informed decisions by identifying cost effective options for transitioning existing UWDS that have minimal socio-economic and technical impact costs on future systems.

CHAPTER ONE

INTRODUCTION

1.1 Background

Urban Water Distribution Systems (UWDS) are the components of Urban Water Systems (UWS) that require the highest budget for future updates and maintenance (Kleiner et al. 2001). If it is possible to minimise the transitioning costs for UWDS, it is hypothesised that maximum cost savings can be made. Transitioning costs are the costs required to change an incumbent UWDS to a future system in tandem to the uncertain pressures such as rapid urbanisation and population growth.

A transition is defined as the shift from one equilibrium point to another through the interplay of the dynamics between the structure, function and form of a system and subsystem (Rotmans et al. 2001). While in urban studies such as the transition to water sensitive cities and cities of the future, the term is used to refer to structural/ infrastructural changes in terms of demographic, economic, social, and spatial structures that are the result of global change pressures such as population growth, anthropogenic changes, urbanization and climate change (Jefferies and Duffy 2011). Transitionability is the characteristic that defines the ease and extent to which the state of a system can cost effectively changed (at minimal technical and socio-economic impact) amidst changing global pressures.

The UWS consists of subsystems responsible for the processes of raw water production and delivery, water treatment and storage and water distribution. Collectively, these components are normally termed as urban water distribution system and they serve to deliver water from the source or point of production to where it is used by man. Unfortunately, to date there is barely any UWDS that is not under pressure to transition (be extended, upgraded or improved). This impetus for UWDS transitions is a result of rapid unavoidable transformations that cities have undergone over the past three decades due to global change pressures. Moreover, management and transition of UWDS will become more challenging than ever due to the anticipated uncertain global change pressures (Jefferies and Duffy 2011; Vairavamoorthy et al. 2012). Due to these pressures, existing UWDS are under pressure to become sustainable. This necessitates among others, lowering the costs and socio-economic impacts (SEI) for changing the systems while adapting the change pressures. This has created a challenge, the so called persistent problem that cannot be eliminated using legacy design principles and conventional optimisation. SEI can be defined as the anticipated effects on the present and future environment due to the implementation of a project (Chadwick 2002).

Despite the anticipated future global change pressures, improvements on the existing UWDS are continuing along the trajectory that increases transitioning costs in the future. Urban water utilities particularly in developing countries lack adequate resources to transition existing UWDS in a sustainable way; upgrades/transitions are still implemented using rudimentary methods based on 19th Century principles. For example, approaches for improving UWDS to respond to change pressures are presented in the literature (Dandy and Engelhardt 2001;Engelhardt et al. 2000; Halhal et al. 1997; Herz 1996; Hong et al. 2006; Saegrov 2005). .Engelhardt et al. (2000) reviewed literature on strategies for maintenance of UWDS. The strategies have been categorized based on (i) model type (ii) nature of cost model and (ii) performance criteria. Of the three strategies the importance to water utilities is based on the cost model because it enables water utilities to optimize the meagre available resources. However, in the past the cost model for maintenance of water infrastructure was skewed toward operation and maintenance costs without considering the impact of interventions of the existing system on the future transitionability. Municipalities and water utilities particularly in developing countries that have the duty to mitigate the rising costs for transitioning UWDS, have instead escalated the problem using incremental reactive and ad hoc interventions on the existing UWDS. These approaches have been rudimentary and tinker with the UWDS. They do not account for the present and future costs for transitioning UWDS. Because these entities are financially constrained within a relatively short planning period, they are still unwilling to finance sustainable transitions where the benefits may not be realized in the medium term. Therefore, they continue to implement conventional design until capacity problems occur which translates into relatively large transition costs resulting in UWDS lock-in. Lock-in refers to social, institutional and technological inertia that creates barriers to the transition of UWDS. Legacy design principles based on the results of infrastructure developments that are most of the time irreversible lead to existing systems becoming themselves barriers to development and transition to new systems. This makes it difficult and even costly to switch the incumbent systems to the desired future systems.

The last two decades have been a period of upgrading UWDS. However, this has been mostly based on the 19th century principles (Vairavamoorthy et al. 2012). During this time, sustainability was not among the design requirements. Drawing from Brundtland Commission’s United Nations Report of 1987, sustainability can be defined as the ability to upgrade and carry on a system with minimal technical and social impacts on the future (OFWAT 2009). This created a situation where the developed designs could not operate on the predicted scenarios but rather have to adapt to the existing conditions for improved efficiency and performance. Based on these approaches, UWDS operated under their capacities or get to their full capacities earlier than predicted. UWDS can be sensitive to both the scenarios of under capacity and overcapacity causing hydraulic problems to the system; a situation that has to be avoided. This yields large sized and complex UWDS with a high degree of geometric and hydraulic lock-in.

UWDS transitions facilitate the alignment of existing systems with new emerging design configurations while at the same time decoupling them from legacy design principles and infrastructure. Designing systems around this concept may encourage much commonality as possible. However, care has to be taken so as not to lock-in the UWDS. Path dependency can minimize system costs while increasing on the other hand transition costs. There is need to obtain the right balance between the level of path dependence to allow into an emerging and/or incumbent system. It is therefore important to assess the impacts of the proposed transition approaches on future transitionability of UWDS under different scenarios and development pressures. In addition, to guide decision making, it is important that transitions are made in such a way to minimise future change costs.

While the benefits of transitionable systems are known, transitioning legacy of UWDS is not always technically, socially and economically viable. There are social, economic and technical benefits in designing systems that can be transitioned easily in tandem with the global change pressures. There is currently a compelling need to minimize the impacts of transitioning UWDS in the future. However, the transition of UWDS continues to lag behind that of urbanisation and population growth. 87 million people in developing countries continue to rely on unimproved water supply facilities; projections estimate that upgrading/transitioning water and sanitation infrastructure will require 400 million and 72 Million US Dollars in developed and developing countries respectively for each of the next 25 years (Zehnder et al. 2003). Transitionability is beneficial particularly when the service life of existing UWDS is due to an end.

Achieving sustainable transitions is a major technical challenge, particularly in urban areas and areas surrounding them. Existing UWDS limit the effort to transition the existing systems to the desired UWDS. Some transitions can be done at a cost while others are impractical or too expensive to implement. The effort and cost of transitioning an UWDS depend on the difference in the characteristics and attributes of the existing system and those of the desired future system. Examples of such characteristics include the geometry, configuration and modularity of the UWDS. A combination of these characteristics determines the transitionability of an UWDS. Thus, transitionability can be used as a design characteristic of UWDS. Because this characteristic is dependent on the geometry and the interaction between the UWDS components, it is easy to understand but its quantification is elusive. Treating transitionability as a design characteristic means that it can best be embedded into an UWDS during design. However, because we are dealing with existing systems, the opportune moment is to embed it in UWDS when upgrading. Due to these pressures, the need for water and water supply systems will increase the need to upgrade the existing system. Thus, upgrades on existing UWDS should also aim to minimise future transitioning cost due to global uncertainties. Upgrading would be a suitable moment to embed the design parameter for transitionability of UWDS. The results of designing UWDS without considering future transitionability include relatively large transition costs for UWDS in the future. Hence water utilities need to revisit the current approach for upgrading and maintaining systems, if future UWDS transition costs are to be minimized.

In order to minimize transitioning costs for sustainable UWDS upgrades, the inertia in the incumbent systems ought to be loosened. This means there is a need for a paradigm shift in the way UWDS upgrades are implemented. This paradigm shift is based on the recent concept of sustainability. For a sustainable future, upgrades or transitions implemented on existing UWDS should be in such a way as to minimise future technical and social impacts. This will ensure that the costs and effort for future UWDS transitions is minimized while maximizing the systems performance. Hence this explains the need to design for UWDS transitionability.

This chapter addresses the objectives, motivation and background of the work undertaken and presents the structure of the dissertation. The chapter acts as a starting point for the proposed approach for designing for urban water distribution systems (UWDS) transitions in tandem with highly unpredictable global change pressures. The research aims to develop methods and techniques to model the relationship and consider minimisation of transition impacts such as technical impacts, operation and maintenance impacts, and social impacts during UWDS transitions. In this context, transitioning is defined as changing and evolving the state and performance of existing urban water systems from where they are to their desired optimized future states. This could be achieved through conventional approaches that are based on the 19th century design principles that consider only operation and maintenance costs or based on paradigm shift that considers transition impact costs and social impact costs in additional to the conventional costs.

1.2 Motivation

The increased nexus between Urban Water Distribution Systems (UWDS) and the society in which they exist necessitates a shift in the focus of design of UWDS from technical systems to socio-technical systems (Allenby 2004). Moreover UWDS transitions are socio-technical systems (Brown et al. 2008) that require integrated socio-technical approaches. Since legacy design principles ignored this perspective, upgrading and transitioning existing UWDS cannot ignore social aspects. However, balancing the socio-technical aspects and the level of renewal (proportion of the incumbent and desired UWDS) is a complex task not only in decision making but also in the required spatial temporal units and measurement scale.

Water utilities are faced with a challenge of continuously transitioning conventional UWDS at minimal technical and socio-economic impact costs. There is a need to minimise UWDS transition impact costs by developing sustainable approaches to guide decision making during the transition of UWDS now and in the future under different scenarios and development pressures. Moreover, the transition of existing UWDS will be more complex due to the anticipated global change pressures such as urbanisation, anthropogenic changes, and population growth that have caused the evolution of existing UWDS into very complex systems. The result is that the transition of these UWDS has become hardly achievable without the use of innovative modelling approaches that reduce future transition costs.

Existing approaches and strategies for upgrading UWDS are investigated in some studies (Engelhardt et al. 2000). However, the existing cost models are skewed towards only operation and maintenance costs without consideration for future transitionability of UWDS. This calls for development of an innovative approaches that departs from the conventional optimisation based approaches that consider only leakage and burst costs during upgrade to considering future UWDS transitionability.

Determinants to the transitioning process are cited in literature (Geels and Schot 2007; Frantzeskaki and Loorbach 2010). They are entrenched in the socio-technical systems: in our culture, habits, institutional and governance structures, market forces, anthropogenic changes, economic behaviours and the infrastructure (Jefferies and Duffy 2011). Models and theory in that can help understand these interactions are existing such as: the multi-level model (Kempet et al. 1998), the multi-phase model (Rotmans et al. 2001), the transition management model (Loorbach 2007). However, these are in other fields and are limited to only a descriptive account of the interactions between the different subsystems that yield UWDS transitions. Hence, there is lack of quantitative models to enable understanding of the socio-technical interactions so as to inform the planning and evaluation of future UWDS transitions in terms of (i) how transitions impact socio-economic characteristics, (ii) the association between socio-economic characteristics and the transition of UWDS. Because there are many socio-economic characteristics, there is a need to identify the most significant variables and to model the impact of the selected independent variables so as to establish the most important predictors of UWDS transitions. Moreover, existing studies for the quantitative design for UWDS is limited to a few urban sub-systems (Sempewo et al. 2010) and hence research is required.

This study is also motivated by a gap in the published literature. In order to identify sustainable transitions that aid and do not limit future transition options, it is required to develop models and approaches that analyse and identify the optimal transition options based on social and technical attributes. One of the main contributions of the study is that it has the potential of improving the conventional practice of upgrading UWDS by merging leakage and burst costs with social and technical impacts in one framework when transitioning UWDS.

1.3 Aims and objectives

The research sets out to develop approaches and techniques for transitioning existing UWDS to the desired future UWDS. These approaches and techniques permit stakeholders to explore effectively the socio-technical costs and impacts of options for transitioning pipes or pipe cohorts. The developed approaches can be used by engineers and planners to evaluate the pros and cons of options for transitioning an UWDS to a desired future system. The aim of this research is to develop approaches to analyse cause-effect relationships of UWDS socio-technical transitions and to develop an approach that merges the resulting social and technical transition impacts with the conventional operation and maintenance costs into one framework when designing for UWDS transitions. If it is possible to minimise the transitioning costs for UWDS based on the developed approach, it is hypothesised that maximum cost savings can be achieved when an UWDS upgrades are implemented with consideration of future transitionability. The specific objectives of the research are as follows:

- To develop a conceptual framework for designing for UWDS transitions and to review UWDS transitions, drivers and barriers.
- To develop a framework and approach to establish a relationship between household socio-economic characteristics and the transition between UWDS options.
- To develop an approach for evaluation of socio-economic impact due to the UWDS transition.
- To develop a methodology for designing for UWDS transitionability that departs from the conventional optimisation based upgrade approaches to considering technical impact costs, operation and maintenance impact costs such as leakage and burst costs and social impact costs

- To test examine and to analyse the sensitivity and performance of the developed approaches on two case studies based on two real urban water networks of Iganga Water and Kampala Water as a proof of concept.

1.4 Research Framework

The research was conducted in six phases. The first phase involved reviewing technical literature. The main emphasis was to act as a thread that ran through all the others levels to underpin aspects and levels of the research. The next phase was modelling of socio-technical transitions of UWDS. This phase involved the use of Chi-square test and Multinomial logistic regression (MNL) to establish the relationship between socio-economic aspects and the transition of UWDS. The third phase was the quantification of UWDS transitions and involved developing a screening tool coded in Visual C++ programming language. The tool uses univariate analysis to compute the technical transition impact index. The index is computed for both a pipe and a cohort of pipes that would minimise future transition costs when retained in a future system. The index is computed by re-optimising a network using a genetic algorithm (GA) based optimisation that is linked with EPANET2 (Rossman 2000) for hydraulic computation. EPANET2 is a tool for extended period simulations for water hydraulics and water quality simulation behaviour within pressurised pipe networks developed by the United States Environmental Protection Agency. On the other hand socio-economic transition impact factor is computed from the most significant socio-economic variables obtained from the second phase. A framework is developed based on multi-criteria analysis and the analytic hierarchy process method widely used for prioritising option. The final phase involved examination of the performance of the developed approaches, testing and analysing the sensitivity of the developed approaches on two case studies: Iganga

Water and Kampala Water both of which are towns managed by the National Water and Sewerage Corporation in Uganda. The case study involved both qualitative e.g. retrospective UWDS analysis and quantitative approaches.

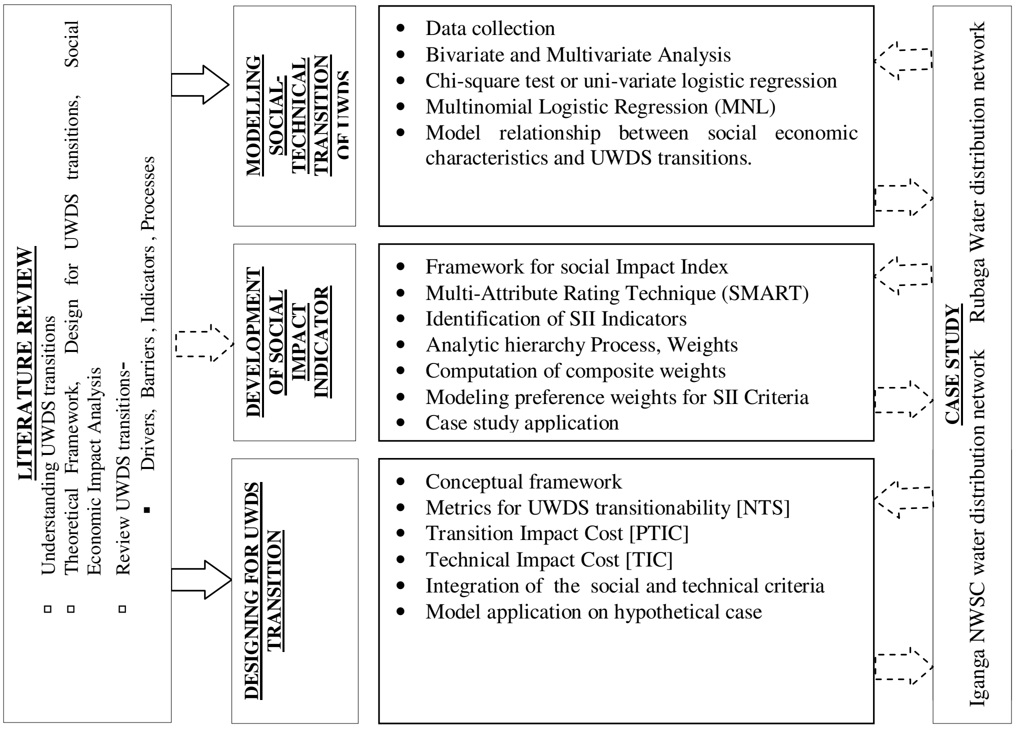


Figure 1-1: Research Framework

1.5 Scope and Structure of the Thesis

Chapter 1 outlines the objectives and scope of the PhD thesis. Chapter 2 reviews the existing theory and models relevant to the transitioning of UWDS. Chapter 3 establishes an approach for quantification of vulnerability/potential for the transition of UWDS based on socio-economic impacts. In this chapter, a framework for analysing and computing a social impact indicator for the Transition of UWDS is presented. The framework is based on the Simple Multi-Attribute Rating Technique (SMART). Weights for the computation of Social transition index are based on the Analytical Hierarchical Process (AHP) technique of pair wise comparison. Chapter 4 presents modelling of Socio-technical transitions of UWDS. It presents a new approach to establish a relationship between socio-economic factors and the transition of UWDS. The model is based on logistic regression analysis to determine the most significant factors that lead to UWDS transitions. Chapter 5 presents a new methodology and model that merges operation and maintenance costs with social and technical impacts in one framework when transitioning UWDS. The approach aims to determine the path UWDS can take to the future under minimal social and technical transition impact costs. The approach is based on the UWDS transition platform whose elements are selected based on the UWDS technical transition impact index and socio-economic Transition Impact index. Chapter 6 presents the application of the case study on Iganga urban water distribution system in Uganda to demonstrate the robustness of the developed model and to test the sensitivity of the developed parameters in an emerging town with weak institutions and infrastructure in its infancy. Chapter 7 presents a case study that demonstrates the application of the developed concepts and models on Kampala Water, a typical case of a city in a developing country with mature infrastructure and functional but rigid institutions. Finally, chapter 8 presents the discussions and conclusions of the main results of the study. The discussions reflect and synthesise the methodological as well as the practical and the theoretical implications of the study. Based on these future research areas are identified and elaborated.

CHAPTER TWO

LITERATURE REVIEW

2. Chapter overview

This chapter reviews literature relevant to understanding, planning and design of UWDS transitions. The design for UWDS transitions can be classified into (i) Transition theory, drivers and barriers (ii) Transition Models and strategies for designing for UWDS transitions (iii) socio-economic impact assessment because UWDS transitions are socio-technical systems. Hence, the literature review was based on the aforementioned three theme areas. The chapter aims to criticise existing approaches, models and tools for the analysis of cause-effect relationships of UWDS socio-technical transitions and the design for UWDS transitions leading to the identification of research gaps. Based on the review, a conceptual framework for the analysis of cause-effect relationships and the design for UWDS transitions is developed.

The review in this section is structured in ten sections. Section 2.1 provides an introduction to understanding UWDS transitions. Section 2.2 reviews the historical perspectives of UWDS transitions. Transition theory is analysed in Section 2.3. Section 2.4 reviews and describes transition decision models that are based on pipe and pipe cohort significance. The design for UWDS Transitions is reviewed in Section 2.5. Section 2.6 reviews and discusses Real Options Analysis (ROA). The UWDS transition platform design and the socio-economic impact analysis for UWDS in reviewed in Section 2.7 and 2.8 respectively. Finally, Section 2.9 reviews approaches for quantification of socio-economic impacts.

2.1 Understanding UWDS Transitions

It is appropriate to define the term ‘transition’ in the current context. Transition is a well-known word so its ordinary usage needs not be reported. The Webster dictionary defines the term as:

> “ *a change from one form or type to another, or the process by which this happens, [...] a passage from one state, stage, subject or place to another [...] a movement, development, or evolution from one stage, or style to another’’.*

Although the term ‘transition’ has been used in many fields (Krueger 2002; Totti 2008) as an attribute to deal with uncertainties that characterise the planning process, until now; few attempts have been made to formally and unambiguously define it for UWDS. Currently, the term is used by water managers and planners of UWDS (Brown and Clarke 2007; Brown et al. 2008) to mean change in water coverage, shift in use of water technology, upgrading UWDS, paradigm shift, change in UWDS structure, function, form or path and change in level of service.

The early works of the terminology dates back to the 19th century when the term was used to describe the transition in the states of substances between solids, liquid and gases (Loorbach 2007). The first definition of the term can be found in the works of Davis (1945) that used the term to describe a transition in levels of birth and death. Since then, numerous definitions have been developed. However, no standard definition exists. Rotmans et al (2001) defined transition for systems as “*the long term continuous change process through which the structure of a system or sub system shifts from one equilibrium point to another through the interplay of the dynamics between the structure, function and form*”. On the other hand in urban studies, the word transition is synonymous to transformation and is used with respect to changing existing urban water systems (UWS) to the desired sustainable UWS regimes through structural/ infrastructural changes (Jefferies and Duffy 2011). Transition was also defined in economics as a shift in the market share or demand for the technologies themselves such as changes in the interaction between the social and technical system. The switch transition manual defines a transition as ‘a radical switch from conventional socio-technical systems to next generation urban water systems’ (SWITCH 2011). Frequently, transitions are described by phases (Brugge 2009), path (Hekkert et al. 2007), and a change in the dynamics (Geels 2002; Rip and Kemp 1998).

It is significant to note that existing definitions of the term ‘transition’ fail to distinguish it from other similar terms that describe the ‘changeability’ of a system over time. Although an agreement on the terminology is elusive, existing definitions agree on the following common characteristics (Rotmans et al. 2001; Totti 2008): a transition involves movement or passage between two states; a transition involves a transformation; a transition involves a process of reorganisation and reorientation of an existing system to incorporate new system requirements literature. Based on the characteristics named above UWDS “transitionability” is the characteristic that defines the ease and extent to which the state of a system can be cost effectively changed (at minimal technical and socio-economic impact) amidst changing global pressures.

2.2 Historical perspectives of UWDS Transitions

This chapter deals with understanding how past urban growth has informed UWDS transitions. The objective is to identify the changes in the urban water management regime and to generate insights into the dynamics of the transitions.

There have been a number of studies carried out on the historical transition of urban water management. Brugge (2009) in his study on the history of water management in the Dutch Water sector found out that changes in the regime were due to the pressures that arose in the 1970s. Whereas the multi-level and the multi-phase model were used to analyse the dynamics of the changes in the structures and actors of the regime, these models are criticised for being non conclusive on the exact cause-effect relationship and the real changes that have taken place in the regime.

Studies by Brown et al (2008) found that urban water management has transitioned into six transition states (Figure 2-1). They include water supply, sewered, drained, water ways, water cycle, and the water sensitive city. The transition states developed due to the need to address emerging water needs, global change pressures (drivers), the available technological options, available resources, strength of the institutions and the governance structures.

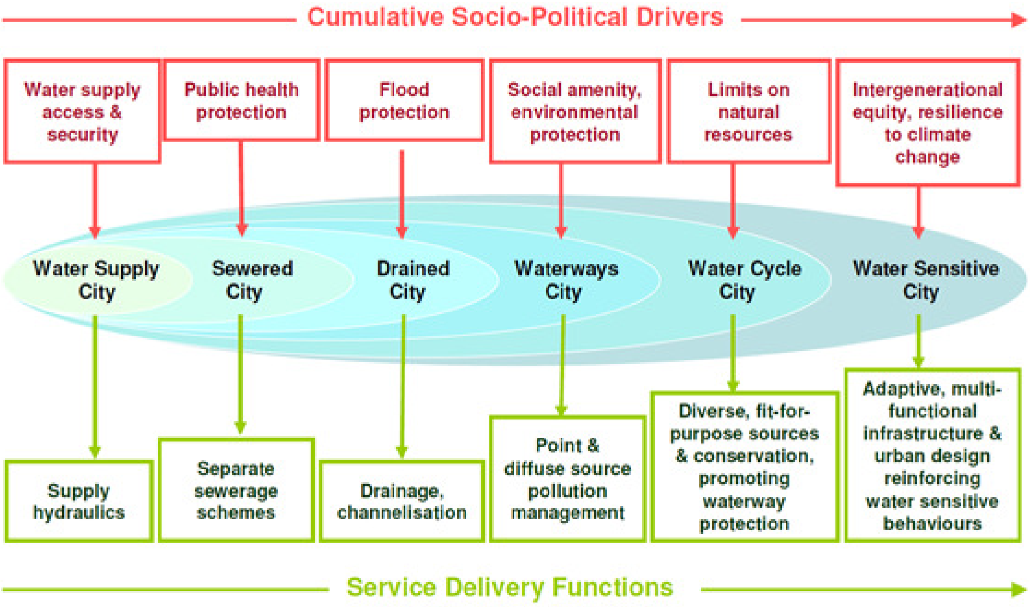


Figure 2-1: UWM transition states (Brown et al. 2008)

The results imply that transitions have been informed by global change pressures (drivers), the available technological options, available resources, strength of the institutions and the governance structures exiting at the time. Although this model is suitable for developed countries, it is criticised for being linear without giving room for leapfrogging some of the developmental stages, a case common to UWDS in developing countries. Hence, UWM in developing countries follow a different path from the Brown transition model which can be classified into four types that include unprotected water sources, protected water sources, yard taps and stand pipes and house connections (Figure 2-2). While the Brown transition model is criticised for not having been tested in other areas, this model can be used to assess the progress of urban water systems in transitioning to the future.

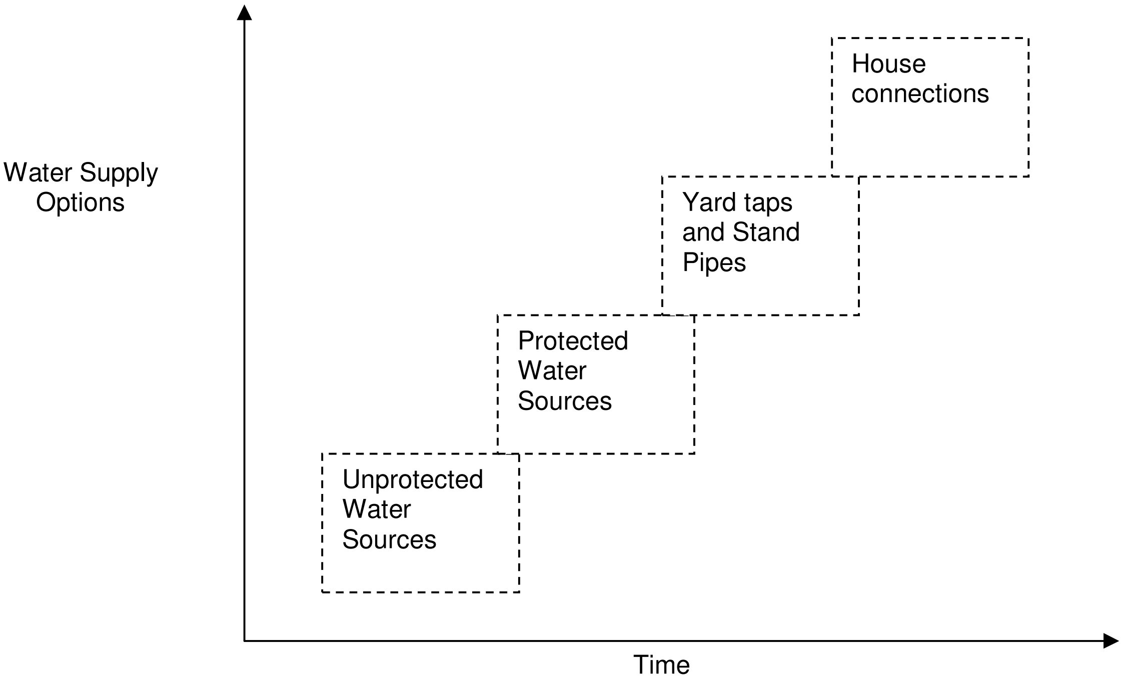


Figure 2-2: UWM transition states-developing country

Gleick (2003) and Dinda (2004) study based on the Environmental Kuznets Curve (EKC) highlights that economic growth and resource depletion are the limiting factors that informed the UWDS transitions process. The EKC (Figure 2-3) describes the relationship between economic growth and environmental impact in form of an inverted U-shaped curve (Dinda 2004; Gleick 2003).

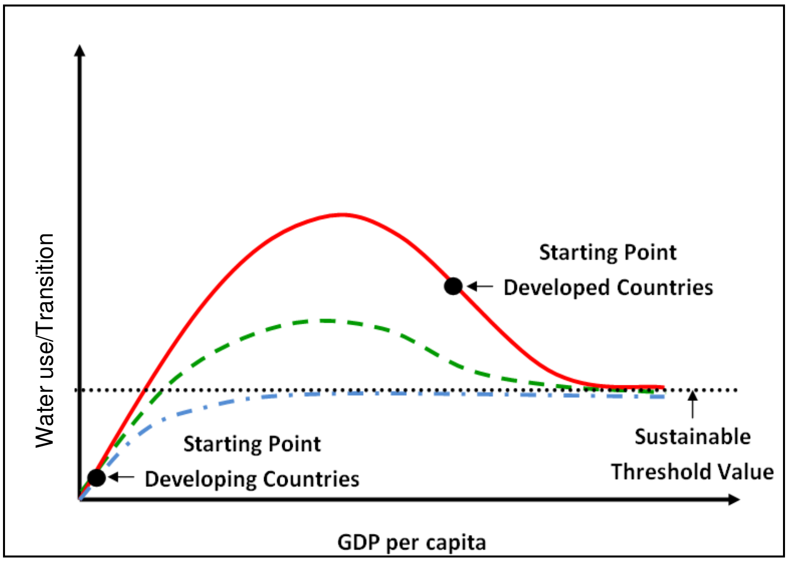


Figure 2-3: Transition based on Environmental Kuznets Curve based on (UNEP 2011)

The main drawback with this model is that it has not been tested and populated with real quantitative data. Moreover it is more suited for the water consumption and management regime and not UWDS. While some authors postulate the EKC as a suitable model to explain UWDS transitions (Newton and Bai 2008), others argue that economic growth does not necessarily account for UWDS transitions (Carson 2010). Although the transition path for developed countries is already developed, that for the developing countries is still in its infancy. This means that developing countries can leapfrog some of the transition steps traversed by developing countries. Hence errors inherent in the conventional transition approach future costs and effort can be minimised.

2.2.1 Driving forces for UWDS transitions

The previous section has presented the theoretical basis upon which the drivers and pressures for the UWDS transitions can be analysed. This section presents the driving forces that have influenced UWDS transitions.

Over the past decades, Brown et al (2008) analysed the drivers for UWDS transitions in the urban water sector. On the other hand Jefferies and Duffy (2011) found out key determinants of UWDS transitions in SWITCH cities. They include (i) the need to meet the changing requirements of societies and (ii) the need to seamlessly switch existing systems to the new innovations in UWDS. SWITCH was a €20 million European Union funded project that aimed to develop innovative sustainable urban water management options for cities of the future. The project that ended in 2011 was demand led and involved 33 partners in 15 countries. Based on SWITCH (2011), the drivers for UWDS transitions were due to economic growth witnessed in the SWICTH cities over the past couple of years. Further more factors that acted as the impetus for UWDS transitions in SWITCH cities included:

(i) Changes in the socio-economic characteristics and anthropogenic changes.
(ii) Changes in the institutional and governance structures.
(iii)Technological advancement and new approaches like semi centralised systems (Bieker et al. 2010; Otterpohl et al. 2002; Schramm and Bieker 2010), smart networks (Otterpohl et al. 2003; Shu 2011), decentralized systems (Gleick 2003; Otterpohl et al. 2003) and flexible urban water systems (Eckart et al. 2010; Huang et al. 2010; Tanyimboh and Templeman 1993; Zhou and Hu 2009) often contribute to reduced transition costs.

However, these require a transition in existing systems, institutions and regulations in tandem with changing requirements.

(iv) New legislation and policy requirements such as the European Union laws and international agreements.

(v) Future change pressures such as unprecedented global change pressures have resulted in the transition of UWDS (Jefferies and Duffy 2011).

Table 2-1: Global initiatives and Paradigms that have acted as drivers for the UWDS

Initiatives/Paradigms	*Period*	*Functionality*
The international decade of Water Supply and Sanitation	(1980-1990)	Focused on safe water and sanitation for all by 1990.
Millennium Development Goals	(2005-2015)	Halve the population without access to Safe Water and Sanitation.
The second water decade (2005-2015) is the international decade for action	(2005-2015)	Decade of action which emphasized community based management championed by women - aimed to halve the population without access to safe water by 2015.
Water Sensitive Urban Design	2005	Promotes of urban planning with the integrated management, of potable water, wastewater and storm water.
Sustainable Development Urban Water Management)	1987	Interventions on the system that meet the needs of today without compromising future transitions.
Integrated Urban Water Management	1944	Managing Water Resources in a catchment as a system.

The limitation of the global initiatives and paradigms is that they focused on increasing water coverage giving less priority to water quality and other aspects of urban water which are mainly due to increased water demand.

2.2.2 UWDS Transition barriers

Scholars in the field of transitioning to urban water management argue that barriers to the transition are not only technological in nature, but can also be socio-economic, governance and institutional in nature (Brown et al. 2009; Brown et al. 2008; Marsalek et al. 2001). Unruh (2000) in the study on carbon lock-in suggested that technological, organisational, industrial, societal and institutional inertia are the main barriers to technological lock-in. These barriers create path dependence that influences transitions. While the study identified barriers to technological lock-in, these were based on carbon lock-in study and not water systems. Studies by Brown and Farrelly (2009) found that socio-institutional inertia are barriers to the transition to sustainable urban water management. However, it is not possible to pin down and enlist the contribution of the different barriers to the UWDS transitions. Drawing from the SWICTH manual, barriers impeding the transition of UWDS particularly in urban and peri-urban areas are presented in Table 2-2.

Table 2-2: Barriers to the transition of UWDS

Serial No	Barrier	Details
1	Lack of knowledge	What ought to be done , which part of the UWDS to begin with , who bears responsibility, who decides, What would be the social and technical consequences of transitioning
2	High transition costs	Initial costs to make existing UWDS transitionable are expected to be high
3	Functional incompatibility	Existing UWDS cannot accommodate the transition requirements
4	Lack of powers to intervene	Lack of policy guidance and standards
5	Legacy infrastructure	Existing UWDS have evolved into complex UWDS with high transition costs
6	Education curriculum	Teaching 19th Century principles to solve 21st Century Challenges
7	Socio-Economic factors	Risk averse implementers/actors/institutions

2.3 Transition Theory

There are three main theme areas for transition and these comprise: (i) analysis of the state of existing systems, (ii) development of options and pathways to the future, and (iii) models.

2.3.1 Analysis of the State of Existing Systems

This theme area is the most widely researched and is found in literature that studies existing urban water systems. For example, UNICEF and WHO (2012) studied the state of water coverage as an indicator of the transition in urban water management. The study was able to assess progress in the Millennium Development Goals. Brugge (2009) used the multi-level model and the multi-phase model to analyse the state of the Dutch water management system. Some studies have analysed the state of urban water management regime. A study by Brown et al (2008) also used the multi-level and multi-phase model to analyse the state of the urban water systems in Australian cities. The applied approaches may suit the UWDS transition problem; however this analysis may benefit from a more qualitative approach rather than a quantitative approach. Mutikanga et al (2011) used performance indicators to analyse the state of existing systems, however their application to the UWDS transition problem is still elusive. Nonetheless, they can act as starting points for the decision making during the UWDS transition process. The analytical tools used to design UWS such as EPANET and a spatial analysis tool, such as Geographic Information System (GIS) can be used to analyse the state of existing UWDS.

2.3.2 Development of Options and pathways to the Future

The objective of studies in this theme area is to identify transition options and cost effective pathways to the future that do not lock-us in. Normally the studies are based on scenario analysis due to lack of quantitative data and approaches to facilitate the prediction of the stochastic trends of future water systems. The future scenarios act as a stress test for the transition of desired options. Butler (2004) for example, proposes four scenarios based on the UK government foresight programme namely. They include global sustainability, world markets local stewardship and provincial enterprise to identify path for desired urban water systems. The provincial state assumes low investment, growth and environmental priority as a result of a decoupling between the state and the international organisations. In the World Markets scenario, fundamental growth in economy and environmentally sound technologies are observed. In global sustainability, there is an increased role of global institutions in defusing the environmental crisis. Lastly, the local stewardship scenario promotes resolution of environmental challenges at the local scale. Whereas the aforementioned scenarios have been applied, they are criticised for being limited to the global, national or regional level and not UWDS at the resolution of the urban scale. Moreover, no analysis has been done to assess how existing UWDS react to the anticipated transitions in the light of the aforementioned scenarios.

2.3.3 Models for designing UWDS Transition

Models are essential for understanding the relationships and complex interaction between components of the UWDS. There are a number of models that can be used to understand and design for UWDS transition. These models can be broadly classified into two groups: (i) Descriptive transition models based on transition theoretical models and (ii) Transition decision models drawn from approaches for upgrading/designing for UWDS transitions. These models are elaborated in the section below.

2.3.3.1 Descriptive transition models

Descriptive models enable an understanding between different actors, systems and factors impacting a process (Ehrenberg et al. 2000). There are a number of descriptive models that have been widely used to understand the cause-effect relationship for different systems (Brown et al. 2009; Rotmans and Loorbach 2009; Totti 2008).

The Organization for Economic Cooperation and Development (OECD 1993), used the DPSIR model to understand the cause-effect relationships between systems and subsystems in infrastructure systems (Fassio et al. 2005; Hamouda et al. 2009). This model (see Figure 2-4) can be used to analyse the cause-effect relationships of UWDS transitions. This enables an understanding of the dynamic relationships between global change pressures and the transition in the state of UWDS due to these pressures. Climate change, economic growth, urbanisation and anthropogenic changes are the drivers that simultaneously generate pressures on the ecosystem. Pressures are the attributes that directly impact the state of the UWDS so as to influence transition decisions. The state of the UWDS presents the condition of the UWDS at the onset of the drivers and the impacts on interacting sub-systems.

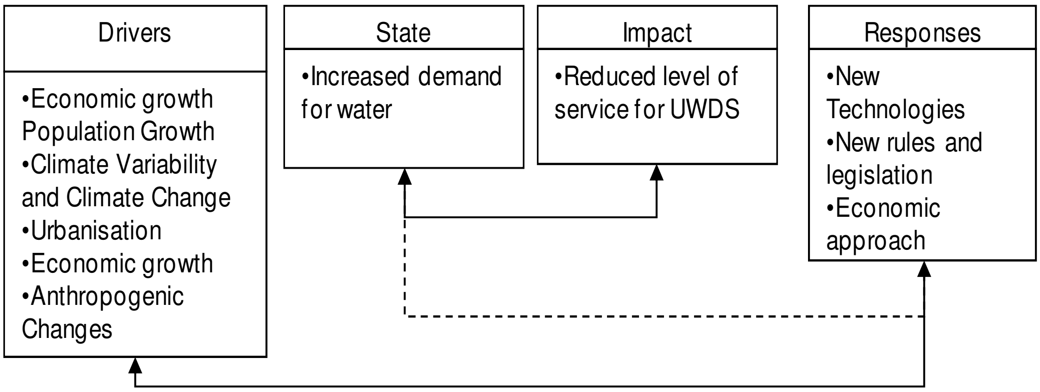


Figure 2-4: Conceptual framework for UWDS based on OECD (1993)

Direct impacts analyse the direct quantity and quality impacts on the UWDS which include increased water demand and need for system modification. On the other hand, responses are the activities implemented on the socio-ecological technical system to make it consistent with the change pressure; for example the transition of UWDS. This model has not yet been applied to the UWDS transition problem.

Some studies used four theoretical transition models that include the multi-level model by Verbong and Geels (2007) and Geels (2002), the multi-phase model by Hekkert et al (2007), the multi pattern model by Van der Brugge and Van Raak (2007) and the transition management model by Rotmans et al (2001) to analyse transitions. These models provide an ambitious attempt to understand and analyse the dynamics and changes in the structure, function and form that lead to transitions. The multi-level model (Geels 2002; Rip and Kemp 1998) provides a framework for analysing UWDS and the interactions between the processes at the niches (micro), regime (meso) and landscape (macro levels) (Brugge 2009) (Figure 2-5)

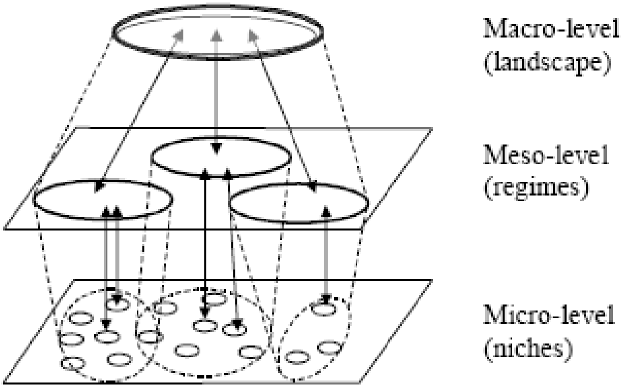


Figure 2-5: The Multi-level model-demonstrates transitions are an outcome of the interactions between the three different levels of a system (Brugge 2009).

The Multi-phase model (Figure 2-6) as presented by Rotmans et al (2001) is a suitable tool to analyse the phases and process of transitioning . Based on the model, the phases are divided into four phases of the transition process. The first phase is the pre-development phase where indicators change only marginally.

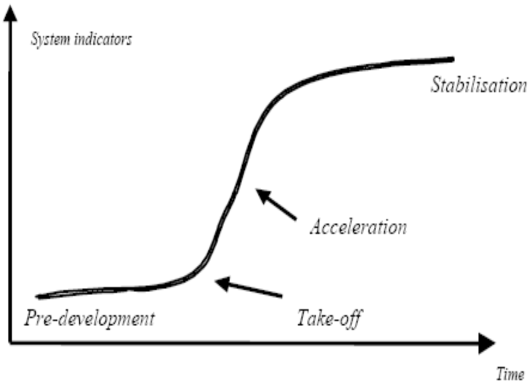


Figure 2-6: The four phases of transitioning (Brugge and Rotmans 2007)

UWDS during this phase experience pressures external to the system such as urbanisation. This phase is followed by the take off stage that arises when pressures continue to act resulting in overturning the capacity limitations inherent in the incumbent regime. During this stage, barriers are overcome leading to the acceleration phase that continues until stabilisation of the future UWDS.

The transition management model (TMM) was introduced by Loorbach (2007). The TMM governs the interactions between the different subsystems to lead to desired urban water distribution systems. The descriptive and prescriptive theoretical frameworks Kemp et al. 2007; Rotmans and Loorbach 2009; Van der Brugge 2009) are elaborated in literature to help understand TMM. The descriptive framework breaks down TMM into three levels. These are strategic, tactical and operational levels to provide a structure and mechanism to implement the TMM process (Figure 2-7).

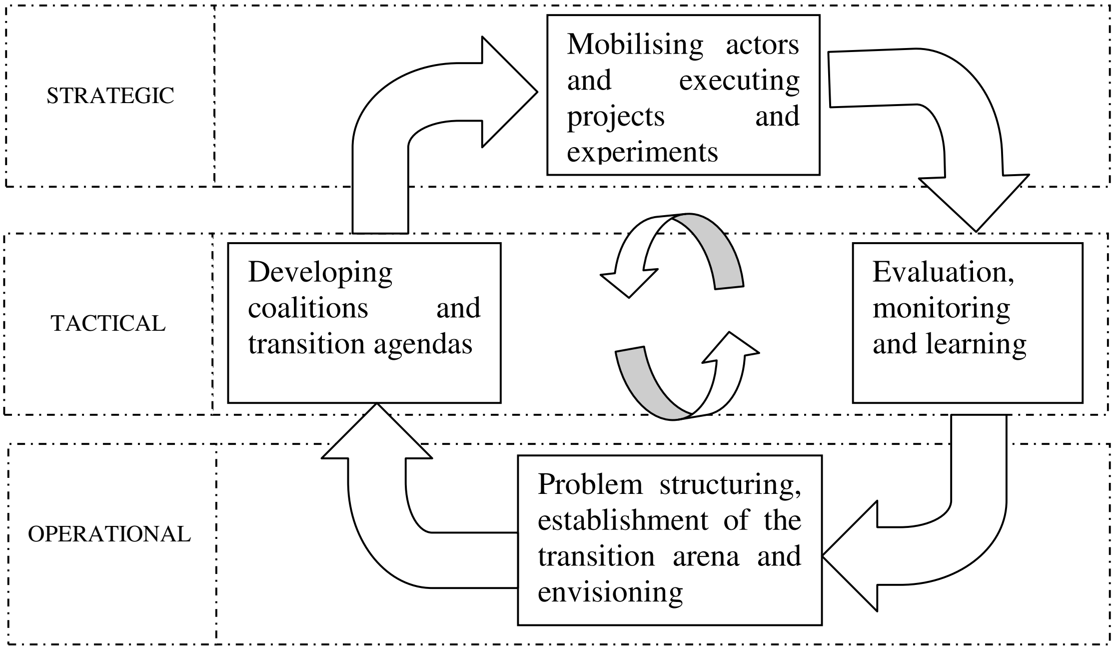


Figure 2-7: Transition management model (Loorbach 2007)

The Multi-pattern model (MPM) originated from solely describing the different patterns of transitions (Rotmans and Loorbach 2009). The MPM aims to describe the different patterns of UWDS transition. The most commonly applied model to understand the patterns of transitioning systems is the transition pathways presented in Figure 2-8.

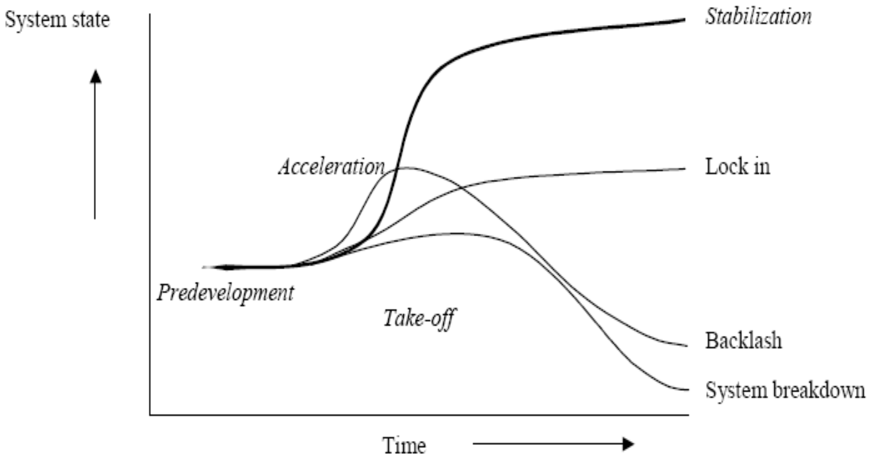


Figure 2-8: Four possible system pathways (Brugge 2009)

While the transition models has been applied to many fields, the application is limited to; water resources (Van der Brugge 2009), urban water systems (Brown and Clarke 2007; Brown et al. 2008) and its implementation in UWDS is still work in progress at its infancy. Moreover, the models have been criticised by Brugge (2009) for lack of well-defined techniques for its application in UWDS and for not having actually been tested in the field. On the other hand Bergman et al (2008) argued that transition frameworks are descriptive and not appropriate for predicting future UWDS transitions. The models do not enable an understanding of the relationships and impact of the different subsystems during the transitioning process. The models are more suitable for descriptive analysis rather than normative UWDS transition analysis.

Other studies have analysed transitions of interacting systems based on a systems approach (Elzen et al. 2004). The systems approach is based on the analysis of the dynamics of how the enabler’s market-forces, push-pull and key actor’s responsible for the transition of different systems influence long-term change. The UWDS transition system consists of social, technical system and institutional sub system. Societal systems include our culture, habits, institutional and governance structures, market forces, anthropogenic changes, economic behaviours (Geels and Schot 2007; Frantzeskaki and Loorbach 2010).

The institutional system entails institutions and Government, which are the main actors in the transitioning process. The institution system enables an understanding of suitable governance and institutional structures required to reconcile conflicts likely to emerge as institutions gain equilibrium during transitioning, values authority, and interests. While governments are instrumental in formulating policy on the desired UWDS, they are hesitant to formulate the policy to enable the transitioning process. As a result, institutions continue to operate in silos as they exercise their responsibilities to deliver services (water, transport, energy) which are counterproductive to the technical transitioning process. It is therefore important to develop appropriate institutional structures and to understand how to transit from existing silo models to a more integrated one (Jefferies and Duffy 2011). Lastly, the technological system reinforces the societal attachment to the legacy infrastructure because new technologies are often contrasted with the old technologies before a transition takes place. Also, the stability and functionality of the societal system is informed and strengthened by the institutional system.

Based on Yezersky (2007) the application of existing theory to the UWDS transition problem faces four shortcomings. The first is that the existing transition models are biased on descriptive analysis of socio- institutional systems and yet an UWDS is a socio- technical system (Hekkert et al. 2007). Secondly, the models focus on the outcome of the interactions (Carlsson et al. 2002; Markard and Truffer 2008). Thirdly, existing transition models are criticised for not considering the interaction at sub system level. Lastly, systems models ignore the impact between the subsystems and fail to establish the most important determinants of UWDS transitions. For effective transitions, descriptive models need to be substantiated with real data.

2.3.3.2 Transition Decision Models

Transition decision models drawn from strategies for upgrading and rehabilitation of UWDS have been reviewed by Fenner (2000) and Engelhardt et al (2000). Still for the purpose of addressing the UWDS transition problem, these approaches are examined as the future transition and socio-economic impacts are often ignored. The models can be broadly classified into: (i) decision based models, (ii) economic based models, and (iii) performance based models. Decision models which are the most widely researched can be classified into four main components: (i) prioritisation models that aspire to identify critical pipes and pipe cohorts for upgrade (Arulraj and Rao 1995); (ii) optimisation models (Dandy and Engelhardt 2001; Walski et al. 1987); (iii) coupled prioritisation and optimisation based models (Vairavamoorthy and Ali 2005); and (iv) multi-criteria approaches (Dandy and Engelhardt 2006; Tanyimboh and Kalungi 2009).

There has been a number of studies on decision models (Engelhardt et al. 2000; IC Goulter 1987) however, these focus on optimisation (Dandy and Engelhardt 2006; Nafi and Kleiner 2009) and not on development of additional objective functions to counter the changing global pressures. Optimisation is the process of evaluating different options based on alteration of system input parameters so as to improve its efficiency (Walski 1982). These models have evolved from linear programming approaches (Alperovits and Shamir 1977; Kessler and Shamir 1989; Quindry et al. 1981) to heuristic and optimisation approaches that are in wide use today. These are based on approaches such as genetic algorithms (Savic and Walters 1997; Vairavamoorthy and Ali 2000), ant colony optimisation (Maier et al. 2003) and simulated annealing (Cunha and Sousa 1999).

Existing models have evolved from single objective problems (Dandy et al. 1996; Goulter 1992a) to multi objective and multi criteria problems (Farmani et al. 2005; Tanyimboh and Templeman 1993). Multi-objective problems generate a compromised solution alternative based on a trade-off between alternatives based on a weighted combination of the many objectives while single problems depend on a singular objective. Although the capabilities of these models are tested and well regarded within the academic circles (Walski et al. 1987) their uptake in practice is still limited. According to Goulter (1992b) and Walski (1985) , the main cause for the low uptake is attributed to the following:

- The models optimize within a system and not across systems. They are limited to specific subsystems and hence do not give a fair representation of reality. Systems such as the social systems are not included in most optimisation models.
- The models are difficult to use and in some cases require data that is not readily available.
- Low skills among practitioners about the optimisation concepts.
- The solutions do not give significant improvement to the existing methods.

Hence greater research that considers UWDS as a socio- technical system is required. Because the majority of decision based models are based on economic based models, development of the model for the UWDS transition problem concentrates on review of economic models of the conventional approaches. A majority of the existing economic based models comprise investment costs (which account for capital costs for pipe replacement) operation and maintenance costs- which account for the repair and maintenance of the UWDS and damage costs (which account for impacts on exiting property and the environment). New legislation guidance from organisations such as OFWAT (2009) requires water utilities in the United Kingdom to improve existing UWDS without compromising the potential for future transitions. This means overcoming inertia in the existing UWDS. However, the aforementioned cost models are skewed towards only operation and maintenance costs without consideration of future transitionability of UWDS. This calls for development of an innovative approach and tool that adds future UWDS transitionability to the conventional leakage and burst costs.

Previous reviews however focus on hydraulic and technical attributes of the UWDS and specifically optimising cost subject to performance constraints. They do not address the UWDS as a socio-technical system and its associated socio-economic aspects. While some studies in UWDS that combine social (Tanyimboh and Kalungi 2008; Tanyimboh et al. 2010) and technical impacts in systems analysis exist, these concentrate more on preferences of communities and investors in selecting between UWDS options rather than analysis of the impacts of transitions on the UWDS in development. These preferences end up being a matter of choice that is considered during the selection of options to implement. In this case, the design is almost done and impacts are already computed. On the other hand, the existing optimisation models that integrate socio and technical aspects focus on water resource management systems at a global level and are not suitable for the UWDS.

Different transition decision models have been introduced. One of them is the prioritisation model that identifies critical pipes and pipe cohorts for upgrade based on pipe and pipe cohort significance for transitioning. This is discussed in the next section.

2.4 Transition decision models based on Pipe and pipe cohort significance

There are three approaches in technical literature that are used to rank the order of significance of pipes based. these are quantity (Ozger and Mays 2003), quality (Wu and Long 2004), and pressure (Vairavamoorthy and Ali 2005). For example, the pipe index ranks the pipes based on its impact on the pressure in the UWDS (Vairavamoorthy and Ali 2005), available demand fraction ranks the pipes based on available demand (Ozger and Mays 2003) and significance index by (Arulraj and Rao 1995) for a pipe is given in equation 2-1

$$PSI_i = \frac{Q_i L_i}{C_i Dia_i} \qquad [2\text{-}1]$$

Whereby;

C_j=Hazen–William roughness coefficients
Dia is diameter of pipe (m)
L is length (m)
Q is the flow of pipe i (m^3/s).

While the transitioning of pipes can be based on either a preventive or a proactive transition plan, the challenge is how to allocate the pipes within the different categories. The fore-mentioned concepts base on the assumption that pipes and pipe cohorts have different degrees of importance in an UWDS. The main drawbacks with these approaches are:

- They do not consider impacts of the pipes on the future transitionability of the UWDS. A pipe that is of importance today may not be important in the future.
- They do not take care of socio –economic impacts and aspects.
- They only rank the significance of a single pipe. The Pipe Index and Pipe Significance Index for a group of pipe could be different given that nonlinear problem.

The approaches used to rank pipes should not be based on hydraulic or technical impacts only but should involve socio-economic impacts as well. The significance of a pipe can be obtained by taking into consideration the following aspects.

- Socio-economic impacts that relates the impact of a pipe or pipe cohort due to a present and future transition on the existing infrastructure, urban form and characteristics and socio characteristics of the location where a transition is to be implemented. The proximity of the pipe in a highly developed and densely populated area definite contributes to the impact of transitioning a given pipe

- Transitionability impacts which is ranking of pipes should provide for the significance of pipe with respect to minimising the cost and effort for transitioning a pipe in the future
- Hydraulic/technical impacts- this approach considers the conventional approaches based on pipe significance and pipe index.

2.5 Design for UWDS Transitions

Sustainability is defined as the ability for a system to be upgraded with minimal impact on the present and future. Based on this definition the upgrades, designs and modifications of UWDS should be implemented in such a way to address the present system requirements without compromising future upgrade impacts and cost. This is because decisions have to be made now even when the future conditions are expected to change. Secondly, we cannot postpone decisions to a time when the future decisions are known. Designing for UWDS transition enables engineers and planners to reuse existing UWDS at minimum cost and efforts. Hence, designing UWDS for transition ensures that future transitions of existing UWDS are economical and do not lock-in the systems.

Despite the fact that the benefits of designing transitionable UWDS are known, these are not always possible depending on the characteristics of the system. These include geometry (Trifunović 2012; Yazdani and Jeffrey 2010), socio economic characteristics (Tanyimboh et al. 2010; Tanyimboh and Kalungi 2009) and the level of performance of existing system.

Because the characteristics of a product are predetermined at the design stage (Boothroyd 1994; Ullman 1994), the capability of an UWDS to transition has to be embedded in the system during the early upgrade and redesign process. However, transitionability is not a straight forward established approach in UWDS design. This is due to the inherent fact that the design of UWDS has been based on 19th century principles that focused on eliminating the existing problems without due consideration to future change requirements. Moreover, the designs were technically biased and gave no consideration to the interaction between the subsystems of the UWDS such as the socio-economic aspects. Currently, the design for UWDS transition lacks relevant literature. However, there are theories and design approaches widely applied in other fields that aim to increase the changeability of products upon which the design for UWDS transition can be based. These include:

(i) design for upgradability (Sakai et al. 2003; Umeda et al. 2005; Umemori et al. 2001)
(ii) design for variety (Martin and Ishii 2002; Fujita 2002)
(iii) design for adaptability (Hashemian 2005; Li et al. 2008).

Designing for upgradability involves extending service life of a product (Umemori et al. 2001) by ensuring that components that reach their technically and economical obsolesce can easily be replaced. The concept has been applied to replace rapidly expiring components of computers in information technology and in designing rapidly upgradable software systems (Hashemian 2005). Because the approach is suitable for rapidly expiring subsystems, it is recommended for specific components of the UWDS that continuously become obsolete due to capacity constraints such as the tank, pumps and valves. Despite the benefits of designing for upgradability, it has hardly been applied to the UWDS transition problem due to two reasons. Firstly, because of lack of suitable approaches and tools for its application in the UWDS problem, the existing tools and methods serve other purposes such as developing an approach for the upgrade of a vacuum cleaner based on function analysis (Ishigami 2003). The second reason is that UWDS are not configured for rapidly replaceable parts. Only few subsystems of the UWDS such as the tank pump and valves are suitable for upgradability. Hence, the approach could be imported in the UWDS transition problem by designing tanks, pumps and valves that have parts that can be replaced in tandem with changing global change pressures. Designing for variety involves development of platforms upon which future transitions can be based.

According to Ulrich (1995), the composition of product architecture determines the attributes of that product. They include product performance, product change, product variety; and adaptability. The constituents of the platform are established through a concept of product architectures (Halman et al. 2003). The elements of the product architecture are established through parametric study and involve trade-offs between performance and commonality. Various approaches used to identify elements of a product platform include parametric studies such as commonality and impacts of the elements on the platform (Dixon et al. 1988), one staged optimisation (where the elements of the fixed and variable components of the platform are established in a single optimisation stage) two stage optimisation (where the fixed and variable elements are established through dual optimisation stages) (Simpson et al. 2001a). While these approaches are well developed, they serve other fields and have not been applied or tested on the UWDS transition problem. Lastly, the design for adaptability is a general term that may be used to mean any of the two approaches. The aforementioned approaches provide a framework for designing UWDS transitions. While the design for future changeability has been used in many fields to generate products from which derivative varieties can be developed, its application in the UWDS transition problem has been limited.

2.6 Real Options Analysis (ROA)

Given the focus of this thesis, an attempt is made to understand UWDS transitions within the scope of real options analysis (ROA). ROA does not cover the entire theory of transitionability. However, it offers a theoretical precept upon which the design for UWDS transitions can be found.

ROA is defined as the right but not the obligation to implement an action at a certain period in time worth a cost that is transferable into real decision options and alternatives (Chen et al. 2009; De Neufville et al. 2006). The approach draws from principles of evaluation of financial options. It involves adopting a proactive approach to the uncertainties that arise. This creates options from which decision makers can choose throughout the life cycle of an infrastructure. Based on the evolution of the future, decisions can be updated when uncertainties in the operating environment become apparent. So in ROA, transitionability is understood as the *'the right, but not the obligation'* to upgrade the UWDS in tandem with the changing requirements in such a way as to minimise future technical and socio- economic impact costs.

The concept of ROA can be found in many works of engineering and infrastructure system design. For example in manufacturing (Bengtsson 2001), product development (Neely and De Neufville 2001), airport design (De Neufville et al. 2008; Smit 2003), hospital infrastructure (Bayer et al. 2007; Maseda 2008) and energy (Rothwell 2012; Siddiqui et al. 2007). Although the studies postulate that designing infrastructure based on ROA results in minimal lifecycle costs and increased value of the infrastructure, these serve other purposes and the approach has yet to be applied to UWDS. The advantages of ROA in contrast to the conventional approach in relation to UWDS transitions are drawn from (Eckart et al. 2010) and these are:

- It advocates for transitionability. Other than the conventional approaches which are skewed towards a deterministic path of an asset during its life, ROA advocates for identification of options that enable transitioning systems when uncertainties become known.
- ROA promotes a proactive response to uncertainties while the conventional approach promotes a reactive response to uncertainties.
- It emphasises the identification of a design platform that can be morphed with minimum impact over time. This eliminates the need to develop a risk free inflation rate that can be used in the conventional NPV design and valuation approaches.
- It is a suitable concept that underpins the design of UWDS transitions. This is because the minimisation of impact costs as well as creation of options for making future changes options unlocks the financial and technical inertia in existing systems.

Recently, ROA has been applied by several researchers to deal with the challenges of designing urban infrastructure systems amidst changing global pressures. Eckart et al (2010) applied ROA in the design of Urban Drainage Systems (UDS) and of Tuttle Hill and Hamburg-Wilhelmsburg. Eckart et al (2010) concluded that the approach yielded the least lifecycle costs in contrast to the conventional approach in the case of uncertainties. This implies that the value of infrastructure can be increased if the design considers options for adapting the future change pressures. However, the approach was based on flexibility and not transitionability. Indeed, the study was not demonstrated on real UWDS case studies. The approach is more suitable for the design of new systems and not existing systems.

Huang et al. (2010) developed a ROA approach to UWDS design and applied it to a hypothetical network. Though the study concluded that it can be applied to UWDS and that ROA enables maximum superior hydraulic performance under uncertainties, the approach had the following short comings. While the study identified UWDS options for dealing with future uncertainties, emphasis was placed on flexibility of pipes and not transitionabilility. It was not demonstrated on a real case study to evaluate its robustness and effectiveness. It did not take care of socio-economic impacts and the product platform concept.

From the review, ROA is gaining widespread acceptance in other fields. However, approaches to implement it for UWDS transition design are lacking. Despite the aforementioned drawbacks, ROA provides precepts such as valuation of infrastructure in changing states and consideration of options for change in the future. These act as a starting point upon which the design for UWDS transitionability can be built.

2.7 UWDS Platform Design

Many water utilities are faced with a challenge of transitioning UWDS from time to time. In mechanical engineering, the concept of product platforms and product varieties is widely applied to reduce the costs for changing components of the system that keep changing over time. This challenge is analogous to the UWDS transition problem. Therefore, the design for UWDS transitions can be sought in the theory of product platform design. A product platform is defined as a set of product components universally designed to respond to rapid changes that occur during the life of the product. The product under concern is one that can be redeveloped with minimal technical and costs impacts (Meyer 1997). The approach is based on the identification of elements with similar characteristics over time. The concept has been applied in many fields to reduce transitioning costs, time and the systemic complexities bound to arise at the onset of future transitions (Gonzalez-Zugasti et al. 2000; Meyer 1997). The approach for the design of product platforms involves identification of a group of components that exhibit similar characteristics under the different scenarios (Farrell and Simpson 2003; Simpson et al. 2001a; Zha and Sriram 2006). The optimal constituents of the elements of an UWDS can be obtained using optimisation with respect to their life cycle transition costs. The challenge is always how to balance commonality and system performance for maximum benefit and minimum cost.

There are two approaches elaborated in literature for identification of platform elements and these are, one stage approaches and two stage approaches. One stage approaches identify both the variable and fixed elements of the platform at once. Examples of the single stage optimisation approach are presented in technical literature. Simpson and D'Souza (2004) and D'Souza and Simpson (2003) introduced a genetic algorithm to solve the problem of identifying the common elements of a product using multi objective optimisation. Otto and Holtta (2007) also applied optimisation to establish the components of a family product based on balancing technical aspects with costs. Simpson et al (2001b) presented an optimisation approach to obtain a trade-off between commonality and system performance. Messac et al (2002); Nayak et al (2002) and Wang et al (2005) implemented the single stage optimisation based on algorithms that maximise performance and minimising cost. These one stage optimisation approaches are criticised for generating computationally heavy loads, particularly when the number of platform elements increases (Wei et al. 2009). In response to this, a two stage optimisation process was presented byWei et al (2009). The approach splits the optimisation process into two stages. The first is to identify the fixed elements of the product platform while the second is to identify the variable elements of the product platform. Hence reducing amount of computational load and the details of the process are shown in Figure 2-9.

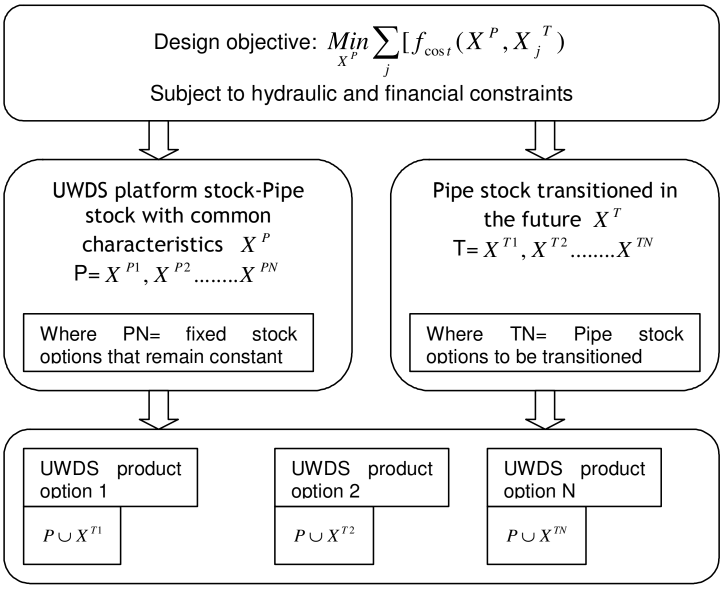


Figure 2-9: Optimisation model for a scale based UWDS product platform modified from (Wei et al. 2009)

Following Wei et al (2009), there can be some commonality between the pipes and pipe cohorts of the UWDS during the transition process. The product platform has been widely used to reduce production costs in an ever changing environment.

UWDS pipes and pipe cohorts that remain fixed during the transition stages form the platform described by the vector X^P of pipes and pipe cohorts. Xj^T represents the variable pipes T of the UWDS transition platform.

The platform optimisation problem can be presented as

$$\underset{X^P}{Min}\sum_j [f_{\cos t}(X^P, X_j^T) \qquad [2\text{-}2]$$

Subject to constraints

$$g(X^P, X_j^T) \leq Constra\text{int} \qquad [2\text{-}3]$$

Whereby

X^P= fixed elements of the platform

X_j^T are the variable elements of the platform

Exploitation of this commonality will minimize UWDS transition costs (Gonzalez-Zugasti et al. 2000). Despite the numerous benefits of the product platform concept, it has hardly been applied to the UWDS transition problem for two reasons. Firstly, it lacks a theoretical framework and tools to enable the design of UWDS transition platforms. Secondly, some approaches and methodologies have been developed and they are yet to be applied and tested.

2.8 Socio-Economic Impact Analysis of UWDS

The concept of sustainability is increasingly becoming eminent in UWDS. As a result, systems analysis of UWDS has emerged as a new paradigm in contrast to the conventional UWDS design. SEIA involves considering UWDS as a socio-technical system rather than only as a technical system. The increased legislation and policy requirement for sustainable development such as the OFWAT sustainability guidance to water utilities (OFWAT 2009) has created an impetus to assess socio-economic impacts due to the design, operation and maintenance and transition of UWDS. However, socio-economic impacts assessment is not a well-developed concept in UWDS.

Drawing from Chadwick (2002), socio-economic impact analysis (SEIA) can be defined as the analysis of the UWDS upgrade and change impacts on the environment. SEIA enables the maximisation of benefits and mitigation of impacts due to the proposed transition. The main reasons that underscore the need to assess socio-economic impacts have been highlighted by the Centre for Good Governance (2006). These include:

- Facilitating sustainable and socially acceptable UWDS are achieved
- Enabling the integration of socio and technical aspects in the UWDS design and transition decision making process
- Mitigating socio-technical impacts due to UWDS transitions
- Protecting society and minimizing impacts on urban infrastructure and the characteristics of urban form.

Besides the improved level of service that comes with UWDS transitions, these changes cause unintended impacts to the society and their environments. Although there is well established literature in transition studies that discusses the relationship between these sub-systems (Brown 2008), the assessment of how the socio system impacts the technical system and vice-versa, and how to couple them with technical aspects is elusive. This means there is need to consider how to assess and embed socio-economic impacts when transitioning UWDS pipes and pipe cohorts. The impacts not only need to be identified and quantified but also need to be optimised. The optimisation should be in such a way as to maximise the performance of the UWDS while minimising the cost and effort of transitioning. These costs should include both socio and technical costs.

Considerable effort has been placed in the development of approaches for assessing socio-economic impacts for development projects. The broad areas through which a project can be assessed have been presented by Chadwick (2002) and include the following broad areas:

- Urban development and urban form
- Population and demographic characteristics
- Changes in aesthetic characteristics
- Local economy
- Urban infrastructure

There are three approaches for the assessment and embedding socio-economic impacts in UWDS. These are the DPSIR approach, multi-objective optimisation approach (MOOA), and multi-criteria Decision Analysis technique (MCDAT). These methods are elaborated below.

2.8.1 The DPSIR Method

Currently, it has become one of the most widely applied methods for SEIA of infrastructure development projects. Bowen and Riley (2003) used the DPSIR method to assess the socio-economic impacts of coastal management based on indicators while Mutenyo (2009) proposed the method as a suitable framework to analyse the impacts to irrigation and hydropower development on Victoria Nile. The major advantage with this approach is that it is participatory and does not require an expert for its implementation. On the other hand, the shortcoming with this approach is that, it has not been applied and tested to UWDS. Thus the approach needs to be improved and adapted to the UWDS transition problem.

2.8.2 The Multi-Objective Optimisation Approach

The multi-objective approach for SEIA involves optimisation of more than one objective in this case the socio-economic impact and another objective with technical connotations. The optimisation process aspires to achieve a solution that balances the two conflicting objective criteria. Multi objective genetic algorithms have been used to undertake SEIA on two case studies (Dandy and Engelhardt 2001; Tanyimboh and Kalungi 2008). Dandy and Engelhardt (2001) applied the method on a discrete zone of Adelaide- Australia; using a single objective genetic algorithm. The SEIA were modelled as failure cost factors introduced as a burst cost factor for land use. The cost objective function was reformulated into a single objective function. The objective function was minimising system repair costs for the existing pipes and the constraints were; the velocity ≤ maximum velocity, the pressure ≥ minimum pressure and funds ≤ funds available funds per budgetary period. Tanyimbo and Kalungi (2008) followed Dandy and Engelhardt's formulation of a failure cost factor to embed SEIA in the long term upgrade of UWDS. This creates great ambiguity and inhibits application of the approach to case specific areas. Hence, evaluation and quantification of socio-economic impacts is required to ensure that impacts due to UWDS transitions are mitigated.

2.8.3 The Multi-Criteria Decision Analysis Technique

MCDAT has been defined by Agudelo et al (2007) as an integrative process that involves identification of indicators, scoring and measuring the indicators, assigning weights, sensitivity analysis and making recommendations (Khatri et al. 2011). The transition of an UWDS involves the analysis of UWDS transition impacts defined by socio or technical impacts. Also SEIA consists of analysis of socio-economic indicators defined for the urban characteristic, urban infrastructure and society demographic attributes. This culminates into a multi-criteria decision problem that involves a suitable approach for solving problems with conflicting and incommensurable criteria. There are many types of MCDAT such as the Analytic hierarchy Process, PROMTHEE, the multi attribute utility theory and TOPSIS that have been applied in other fields (Mateo 2012). Although the MCDAT have been widely applied for sustainable water management (Foxon et al. 2002; Giupponi et al. 2004; Van Moeffaert 2002), its application for SEIA in UWDS is in its infancy. The few incidences are when it has been applied to embed SEIA in UWDS (Tanyimboh and Kalungi 2008; Tanyimboh et al 2010). Tanyimboh and Kalungi (2008) and Tanyimboh et al (2010) presented an approach for assessing social and environmental impacts for UWDS on a water distribution network for a peri urban area in Blantyre- Malawi. They applied the AHP to determine the weights for the performance, economics, socio and environmental impacts. Several measures were used to assess the socio and environmental impacts such as acceptability, affordability and health sub-criteria Tanyimboh and Kalungi (2008). Whereas the multi-criteria approach was successfully applied as a suitable approach for SEIA, it is criticised for the following:

(i) Not capturing long term impacts during the decision making process.
(ii) The attributed and measures used are just the preferences of the communities and not the impacts of the implementation of the UWDS upgrades.
(iii) The approach was applied posterior to the actual design of the UWDS in form on evaluation of design options and analysis.
(iv) They are subjective and hence prone to manipulation.

Therefore, there is a need to develop approaches that can enable the application of MCDAT for SEIA.

2.9 Quantification of Socio-Economic Impacts

Quantification of socio-economic impacts is an outcome of the application of SEIA to the UWDS design and transition problem. There are two approaches for quantifying environmental impacts and these are qualitative methods and quantitative methods. Although these methodologies have been applied in integrated water resources management and sustainability, they have hardly been applied to the UWDS transition problem.

The qualitative approach is a suitable methodology for analysing cause-effect relationships based on the questions of why and how impacts occur. The method is based on expert opinion and on consultation with key stakeholders to undertake the analysis and is based on the DPSIR model elaborated in Section 2.3.1. However, the approach is criticised for being descriptive and not providing a quantitative model of the impacts relationship between the changes in socio-economic characteristics and the transition of UWDS. Moreover, the application of the qualitative approach is limited to other systems other than the UWDS.

The quantitative approach is an effective approach for measuring socio-economic impacts. It is one of the most widely applied approaches in the quantification of socio-economic impacts. Quantification of socio-technical impacts is based on socio-economic indicators (Bowen and Riley 2003). Methods to quantify these indicators can be through one of the following approaches:

- Data mining and statistical methods of existing data if available,
- Adopting indicators from similar studies,
- Applying theoretical information about the characteristic of the indicator,
- Trend analysis and logical deductions.

However, quantification of socio-economic impacts using indicators is a complex problem. While some indicators are crisp (e.g. population density), others are not easy to quantify such as level of urban development. In such cases linguistic terms are used on the linkert scale or fuzzy based approaches. Because the indicators are to be used to compare design alternatives, absolute values of the indicators will not be required.

The limitation with the quantitative indicator method is that it is developed without considering the interactions between the different subsystems. For example Bowen and Riley (2003) developed socio-economic indicators that did not consider the interaction between the two subsystems. Similarly, Brent and Labuschange (2006) developed social impact indicators that also did not consider the interactions. Other works developed conceptual frameworks for these indicators such as the sustainable development indicator developed by (Bowen and Riley 2003). Examples of these indicators are presented in literature. However, these serve other purposes and are more suited for the specific sectors: Guio -Torres (2006) developed a sustainability indicator. However, the indicator was for UWS at the system level. Carden et al (2009) developed a sustainability index for integrated urban water management. The limitation with this indicator is that the socio dimension used to generate the indicator refers to socio acceptability rather than socio impact. Other indicators are environmental sustainability indicators (Lundin and Morrison 2002). The limitations with the afore-mentioned approaches are:

(i) They do not consider the interactions between the socio and technical system

(ii) The methodology and socio-economic impact indicators have some limitations of being applied in developing countries

(iii) The need for sufficient data that is not readily available in most areas such as in developing countries.

Through development of an indicator for socio-economic impacts, planners, engineers and socio-economists are able to gain insights on the impacts of the different options for designs and upgrades on the urban environment. Hence, being able to prioritise areas for transitioning based on anticipated impacts versus benefits.

CHAPTER THREE

DEVELOPMENT OF A SOCIO-ECONOMIC IMPACT INDICATOR FOR UWDS TRANSITION

3. Chapter overview

Prior to transitioning UWDS amidst scarce resources, decision makers such as government bodies, municipalities and water utilities need to be aware of the socio-economic impacts in the urban area. However, evaluation of socio-economic impacts due to the transition of UWDS is a technical challenge involving multiple and conflicting criteria and many different actors with conflicting interests. Moreover, the existing approaches for computation of socio-economic impacts when upgrading UWDS are more of a post-design rather than pre-design exercise. In this chapter therefore, a multi-criteria framework for analysing and computing a Socio-economic Impact Indicator (SII) - a measure of the impact of UWDS transitions on urban characteristics of an area- is presented. The SII is based on the aggregation of indicators for the different dimensions which include; the Urban Characteristic Impact (UC), the Urban Infrastructure Impact (UI) and Socio-economic Impact (SE). The Analytical Hierarchical Process (AHP) technique (Saaty 1980) was used within the framework to compute weights of the SII at the three hierarchical levels. The robustness of the developed approach is demonstrated on computation of SII for UWDS transition zones for Iganga and Kampala (some of the branches of National Water and Sewerage Corporation in Uganda). The developed methodology can be used to analyse the socio-economic impacts of UWDS transitions on an urban area. The approach can enable planners and engineers of water utilities and city authorities to identify UWDS transitions zones with high and low socio-economic impact. Thus, the approach enables the selection of options for transitioning UWDS that minimize transition costs due to socio-economic impacts.

This Chapter is structured in eight sections. Section 3.1 introduces and gives a brief overview of the study undertaken. Section 3.2 reviews and describes the Multi Criteria Decision Analysis (MCDA) technique. The Analytic Hierarchy Approach (AHP) used to model preference weights for SII Criteria and Sub criteria is described in Section 3.3. Section 3.4 describes the framework for development of the socio-economic transition impact index (SII) disaggregated into three levels of the indicator, the dimensions and sub criteria levels. Section 3.5 presents the application of the developed framework is applied to compute the SII of UWDS transition zones in Iganga and Kampala case studies as a proof of concept. Finally, Section 3.6 discusses the results of the study.

3.1 Introduction

The sustainable transition of UWDS is a major technical challenge particularly in urban areas. Also, existing UWDS has been built using 19th century principles and currently they are not able to meet the required levels of service. As a result there is need for enormous investment to transition existing UWDS in tandem with the aforementioned change pressures. For example, it is estimated that transitioning water and sanitation infrastructure will require US$10 trillion in 25 years in developed countries and US$1.8 trillion in developing countries (Zehnder et al. 2003). Prior to making investment decisions, designers and planners need to assess the potential socio-economic impacts due to UWDS transitions in an urban environment.

UWDS transition is a socio-technical problem (Brown et al. 2008) that requires not only assessment of technical impacts but also evaluation of socio-economic impact (SEI). The integrated analysis of technical and socio-economic attributes of urban infrastructure is gaining acceptance as a sustainable design approach (Allenby 2004). Whereas SEI is a key decision criterion to achieving future UWDS transitions that are sustainable (Brown and Clarke 2007), decision makers in municipalities and water utilities particularly in developing countries often lack a methodology for its quantification. Hence, the degree to which such assessments are implemented in the UWDS design process is limited. SEI is about assessment of the potential impact on the urban population and environment due to the transition of an UWDS. The majority of conventional approaches to SEI are qualitative focusing on cause-effect relationships of the socio-economic impacts. The conventional way of implementing SEI based on cause-effect relationships is unrealistic as it does not enable the quantitative evaluation and analysis of the UWDS transition option. This makes it unsuitable for the evaluation of future transitions options.

Recently, there has been increasing efforts for quantitative analysis of SEI during the upgrade of UWDS (Tanyimboh and Kalungi 2009). However, these studies are generally limited to post design SEI analysis rather than a pre-design analysis. The design is almost done and the impacts are already computed. For example, Tanyimboh and Kalungi (2009) considered SEI aspects for the upgrade of UWDS but they were limited to the preferences of communities and investors in selecting between UWDS options after design rather than the analysis of the impacts prior to the design of UWDS. Clearly, the aforementioned works are not sufficient to compute the overall SEI due to UWDS transitions in an urban area. By analysing the SEI, decision makers can be able to gain insights on the magnitude of potential impacts of different UWDS transition options in an urban area. This will enable decision makers prioritize UWDS transition options based on SEI costs.

Multiple criteria decision making (MCDM) or multiple criteria decision analysis (MCDA) is a tool used in decision theory and analysis to solve problems involving many decision-criterion and decision-makers (Al-Harbi 2001; Mendoza and Martins 2006; Koksalan et al. 2011). They use judgments from decision- makers to prioritise options based on weights and ranks generated from a set of evaluation criteria (Belton and Stewart 2002; Kiker, Bridges et al. 2009; Mutikanga et al. 2011). Mendoza and Martins (2006) described the attributes that characterize MDCA problems. They include structured approaches, the presence of more than one decision-criterion; and the decisions based on judgments of many decision-makers. It is these same attributes that make MCDA or MCDM a suitable approach to the development of SII. This is because they address the issues related to the SEI quantification problem. These include: (a) the need for a structured approach for the integration of the different dimensions of SII a measure of the SEI; (b) the fact that quantification of a SII involves multiple decision-criterion such as the Urban Characteristic Impact (UC), the Urban Infrastructure Impact (UI) and Socio-economic Impact (SE); (c) the presence of decision-makers such as engineers, planners and socio-economists with conflicting views on the priorities and weights of the dimensions and criteria in the computation of SII. Moreover, MCDA or MCDM has additional features that make it an appropriate tool for solving complex problems such as analysing SII. First, the MCDA/MCDM methods can take care of both quantitative and qualitative data (Mendoza and Martins 2006; Mutikanga et al. 2011). The data for the dimensions and criteria required to compute SII may be both quantitative (for example, population and population density) and linguistic in nature (e.g. level of urban development, local economy) while others may be limited or with a high degree of uncertainty. Thus, the unique ability for MCDA/MCDM to take care of these mixed data through judgements from decision-makers makes them appropriate tools. Secondly, the MCDA/MCDM is structured in such a way as to accommodate the views and inputs from the different stakeholders and decision-makers (Mutikanga et al. 2011).

Recently, there has been a review of the application of MCDA in water resources planning and management (Hajkowicz and Collins 2007; Hajkowicz and Higgins 2008). Whereas, the same review indicates water supply planning and infrastructure selection as the area with the highest MCDA application, previous MCDA techniques have been based on indicators that serve other purposes such as technical, cost, heath and water quantity. In addition, existing applications of MCDA on urban infrastructure systems (UIS) are focused on urban infrastructure system and other indicators other than SEI. For example, Khatri et al (2011) applied MCDA to compute performance indicators for UIS in an urban environment. Similarly, Zarghami et al (2008) and Van Moeffaert (2002) developed and applied sustainability indicators for the urban area based on MCDA. De Carvalho et al (2009) applied the MCDA for computation of sustainability index. The approach is based on the aggregation of the multi-dimensional assessment of the physical, institutional and social subsystems of a city. The approach has been used to assess the extent to which cities meet their targets for achieving sustainable integrated urban water management. The approach and index has already been tested on the Southern African cities of Maputo and Hermanus (De Carvalho et al. 2009). The results are positive and the proposed approach can be expanded on to create an integrated approach to analyse SEI due to UWDS transitions. The approach recognizes the data limitations that are common in developing countries. Whereas this approach serves to track progress of cities towards urban water management sustainability, it can be built on to develop a SII applicable to UWDS transitions. Although these approaches address MCDA approaches in an urban area, they do not tackle the issue of SEI that is essential to achieving sustainable UWDS transitions. Clearly, there remains a gap with respect to application of MCDA techniques for SEI in an urban area.

In this chapter, a MCDA framework for analysing and computing a SII is proposed to aid decision-makers of water utilities and municipalities in identification and prioritisation of UWDS transition options based on minimisation of SEI. The framework is based on a systems approach and decomposes the UWDS indicators into three hierarchies, the dimensions and sub criteria levels. The framework begins by analysing the social impact sub-criteria generating metrics and indicators, combining these indexes to produce an overall SII. The Analytical Hierarchical Process (AHP) technique was used within the framework to compute weights of the SII at the three hierarchical levels. The robustness of the developed approach is demonstrated on computation of SII for UWDS transition zones for Iganga and Kampala some of the branches of National Water and Sewerage Corporation in Uganda as a proof of the concept.

3.2 Multi-criteria Decision Analysis

Solving challenges of real world problems such as development of a composite SII involves many decision-criterion and decision-makers. Decision making in such a scenario is a complex task that requires appropriate tools that enable the trade-off between the conflicting criteria from different decision makers. Multi-criteria decision analysis (MCDA) is a technique used to solve problems involving many decision-criterion and decision-makers. Mysiak and Giupponi (2005) defines MCDA as a decision making technique suited for problems with a finite set of decision options and with multiple and conflicting criteria in different units. MCDA techniques are recommended for decision problems with more than one conflicting decision-criterion, involving different measurement units which can be qualitative and quantitative, decisions that require judgements from many decision-makers with conflicting evaluation criteria and objectives, and decision-criteria involving ranking and weighting of multiple evaluation criteria (Mendoza and Martins 2006).

MCDA methods have been classified differently by various researchers. Triantaphyllou et al (1998) classifies MCDA methods based on data type such as deterministic, stochastic, or fuzzy and number of decision makers such as single or group MCDA methods. However, the classification of these methods into Multiple Attribute Decision Technique (MADT) and the Multiple Objective Decision Technique (MODT) (Kabli 2009) are the most widely applied. Though the methods are diverse, most involve similar generic steps described by Triantaphyllou et al (1998). They include defining the problem in a hierarchical order, determining the criteria and sub-criteria, modelling preference weights for the criteria and scoring the criteria and modelling the decision matrix to rank each alternative. The aforementioned steps will be applied to the development of a SII. According to Al-Harbi (2001), the utility of MCDA is in the area of design and evaluation which is analogous to the SEI problem.

The MADT assumes the decision options are known whereas the MODT assumes that the decision alternatives are not known and are judged based on how close they meet the design objectives. According to (Kabli 2009) the problems solved by MCDT are broadly classified into three categories:

i) Selection techniques based on goal and baseline models to identify the most unsuitable alternatives that do not meet the decision maker’s requirements. Such methods include the Step Method (STEM) and the Technique for Order Preference by Similarity to Ideal Solutions (TOPSIS).

ii) Sorting techniques that aggregate criteria into a single indicator which is used to choose technological strategies or options. For example, The Multi-Attribute Value Technique (MAVT), Multi-Attribute Utility Technique (MAUT) and The Analytic Hierarchy Process AHP.

iii) Ranking techniques used to prioritize between different alternatives. Examples of such methods include the method for Elimination and Choice Translating Reality (ELECTRE) and the Preference Ranking Organization Method for Enrichment and Evaluation (PROMETHEE).

The MCDA problem can be presented mathematically as determination of the optimal alternative with the highest score A $_{\text{optimal}}$ from a finite set A of decision options { $a_{1,}$ a_2,……….a_m} based on a finite set G decision criterion { $g_{1,}$ g_2,………g_n}. This can be simplified into an evaluation matrix EM (Eqn 3-1) of N alternatives and M decision-criterion both of which should always be greater than two (Hajkowicz and Higgins 2008)

$$EM = \begin{bmatrix} g_1a_1 \ldots\ldots g_na_1 \\ . \\ . \\ . \\ .g_1a_m \ldots\ldots g_na_m \end{bmatrix} \qquad [3\text{-}1]$$

The priority of the decision-criterion requires a vector W of m weights {w_1, w_2….w_m} assigned by the decision-makers. Aggregation of standardised scores for the decision-criterion with the weights produces a composite value that can be used to analyse the performance of the different alternatives.

Although MCDA methods have been widely applied for water resources planning and management, the majority of the recent applications of MCDA are in water policy evaluation, water supply planning and infrastructure selection (Hajkowicz and Higgins 2008). Recently, there has been a review of the application of MCDA in the water supply planning and infrastructure selection domain (Hajkowicz and Collins 2007; Hajkowicz and Higgins 2008). However, their application in UWDS and for the development of SEI is in its infancy. Moreover, while the same review indicates water supply planning and infrastructure selection as the area with the highest number of MCDA applications; previous MCDA techniques have been based on indicators that serve other purposes. MCDA have been widely applied in practice over other methods for being easy to understand and able to take care of these mixed data and to accommodate the views and inputs form the different stakeholders and decision-makers in a systematic, transparent and coherent way. For these reasons, MCDA has been selected for the SII problem. However, MCDA suffers from a few drawbacks that potential users ought to be aware of which include their subjectivity, risk of being manipulated, the approach is prone to rank reversal when new criteria are introduced and potential of creating “black box” effects where criteria exceed seven, limiting the decision-makers ability to objectively track the decision process (Mutikanga et al. 2011).

This study aggregates various indicators for the different dimensions of the urban impacts due to UWDS transitions. Thus, one composite index (SII) is generated. Aggregation of the indicators at the three hierarchical levels is based on MCDA technique. On the other hand, AHP (a mathematical model) is used within the framework to allocate weights to decision-criteria during the multi-criteria decision-making process.

3.3 The analytical hierarchy process (AHP)

AHP is a simple technique that has been widely applied to decode views from experts where multiple and conflicting criteria exist. The AHP technique was developed as an analysis technique introduced by Satty (1971). The technique has been widely applied in urban infrastructure planning and design projects such as UWDS (Tanyimboh and Kalungi 2009; Khatri et al. 2011) among others. The technique synthesizes complex problems by decomposing them into different levels based on a hierarchical structure (indicator, criteria and sub-criteria) and establishes the weight of each indicator. The priority and weight of each indicator in AHP is generated based on pair-wise comparisons which reflect the decision-makers preference between two options of a given criteria. The AHP technique is usually the preferred approach for MCDA for a variety of reasons such as: (i) ease of application; (ii) ability to ensure consensus during the decision making process; (iii) is more objective when obtaining the weights for different indicators; (iv) ability to reduce bias in decision making by checking inconsistencies; and (v) capability to generate scales where decision-criteria lack measures (Bayazit 2005; Meade and Presley 2002; Millet and Wedley 2003; Triantaphyllou et al. 1998).

It is these same attributes that the AHP technique was selected to weigh and rank the priorities at all hierarchical levels of the SII. However, the approach is not free from criticisms which cause ranking irregularities that should be informed to potential users. These include risk of experiencing rank reversal ability to lose important information through the aggregation process that compensates good and bad scores on some criteria and ability to suffer "black box" effects particularly when the number of pair-wise comparisons (n) become extremely large (n(n−1)/2). There is also lack of a theoretical basis to underpin them (Ai-Harbi 2001) and the use of Saaty's nine point scale making it difficult to distinguish criteria whose magnitude is greater than nine (Bayazit 2005; Jin and Zhang 2002; Macharis et al. 2004). Nonetheless, the approach is still upheld as technically valid and helpful for weighting and prioritisation in MCDA (Bayazit 2005).

Based on Saaty (2008), steps of AHP technique applied for weighing and ranking priorities at all hierarchical levels involve the following:

(i) Construction of a judgment matrix

The judgment matrix is constructed through pair-wise comparison which is in effect the deviation in the rank of the priorities between two decision-criterions. The pair-wise comparisons are undertaken by stakeholders by evaluation of how many times or by how much one decision criterion is more important than the other. These comparisons between criteria are undertaken using Saaty's (1998) intensity scale shown in Table 3-1 and entering the result into a pairwise judgement matrix.

Table 3-1: AHP Scale

Scale Value	Relative importance	
1	Equal	Equally favoured
3	Weak	Weakly favoured
5	Strong	Moderately favoured
7	Very strong	Strongly favoured
9	Absolute	Absolutely favoured
2,4,6,8	Intermediate values	

The matrix that results from the comparison takes up the number of elements being compared. For example for three criteria the resultant matrix is a 3 x 3 matrix.

(ii) Determination of the priority vector

The priority vector is determined through the hierarchical synthesis of judgment matrix to obtain a normalised matrix based on a variety of mathematical approaches applied in practice including the geometric mean, mean transformation and eigenvector method (Kabli 2009). In this chapter, the geometric mean approach has been applied. For instance, the first element of the criteria and sub- criteria priority vectors is computed from the mean of the row of the normalised matrix. Hence, the first element of the normalised matrix is obtained by dividing the first element of the judgement matrix by the total of the column in which the element falls.

(iii) Examination of the consistency of the judgment matrix

Because discrepancies often occur between the comparison results and the decision, Satty's consistence ratio $CR_{JM} = CI / R_{CI} * 100$ is used to check the inconsistence that may arise during the process of pair-wise comparison where CR_{JM}=consistence ratio for the judgement matrix, CI= consistence index- a measure of consistence and R_{CI}=random consistence index

$$CI = (\bar{\lambda}_{\max} - n)/(n-1) \qquad [3\text{-}2]$$

$$CR_{JM} = CI / R_{CI} * 100 \qquad [3\text{-}3]$$

Where $\lambda_{\max}$ = largest eigenvalue of judgement matrix and

$\bar{\lambda}_{\max}$ = Average eigenvalue generated from average reciprocal matrices.

Table 3-2 gives the RCI values used to check the consistency of the judgement matrix. A judgement matrix was validated using the consistence ratio that should always be less than 10% (Saaty 1980), as represented by the equation [3-4]

$$10\% \leq CR \geq = n \qquad [3\text{-}4]$$

Table 3-2: Random consistency indices (Saaty 1980)

Matrix	1	2	3	4	5
RCI	0	0	0.58	0.9	1.12

3.3.1 Simplified example of AHP

A simplified example for the application of the AHP process in Section 3.3 is presented for demonstration purposes. Assume the weights of three SII indicators A, B and C are to be computed using the AHP technique described in Section 3.3. The following can be done to generate the priorities of SII indicators.

Construct judgement matrix

The first step is the construction of n x n judgement matrix. The entry of row i and column j represents how much indicator i is more important than indicator j in affecting the SEI of an urban area due to transitioning an UWDS using Saaty's nine point scale. The decision-makers DM1, DM2 and DM3 have to indicate their preference for the indicators and how it contributes to the SII as shown in Table 3-3. Assume DM1 has identified the following judgement matrix for the SII indicators.

Table 3-3: Judgement matrix for SII indicators

DM1	A	B	C
A	1	3	6
B	0.33	1	5
C	0.17	0.2	1

Whereas, preferences of individual decision-makers have been enlisted using pair-wise comparison, the aim of this stage in the framework is to encode priorities for the entire group of the planners (UP), engineers (UE) and socio-economists (USE).

Two approaches are widely applied in literature to aggregate the opinions of a group. The first one is Aggregation of Individual decision-maker judgements (ADJ). Individual pair-wise comparisons are first aggregated prior to synthesising the judgement matrix to generate weights. The second is Aggregation of individual decision-maker weights (ADW); where priority weights of every decision-maker in a group are first generated and then aggregated (Forman and Peniwati 1998). The arithmetic mean and the geometric mean are commonly applied to aggregate group preferences for both aggregation levels (that is, ADJ and ADP) (Mikhailov 2004). Here ADJ approach has been used to generate the weights for all the decision-maker in the group. As discussed by Forman and Peniwati (1998), the geometric mean is recommended for ADJ approach while arithmetic mean and the geometric mean are suitable for both ADJ and ADP. In this chapter, the ADJ approach (Equation [3-4]) is used to aggregate individual judgements of the decision-makers in a group.

$$DMa_{i,j} = \left(\prod_{DM=1}^{N_{DM}} a_{i,j,DM} \right)^{1/N_{DM}} \qquad [3\text{-}5]$$

where: $DMa_{i,j}$ is the preference of a group of decision-makers DM with respect to pairwise comparison of criteria i and j, a $_{i,j,DM}$ is the DM numerical AHP scale value (see Table 3-1) assigned to the pairwise comparison of criteria i and j while N_{DM} is the number of respondents in a decision-making group considered in the study.

As noted by Forman and Peniwati (1998), the ADJ approach enables the elimination of inconsistent responses of the decision- maker, stresses that the group of decision-makers act as a group and saves the computational time as the AHP is applied once when generating the group priorities of the decision-makers. The influence of the individual decision-makers within a group was assumed equal, whereas in reality decisions of leaders in a group often have a higher weight than other member in a group. Table 3-4 shows an example of a pair-wise comparison matrix in which the judgement matrix of the group decision makers are aggregated based on (Equation [3-4])

Table 3-4: Generation of judgement matrix for a group of decision makers

DM	A	B	C
A	Average [UP_{AA1}-UP_{AA_NDM}]	Average [UP_{AB1}-UP_{AB_NDM}]	Average [UP_{AC1}-UP_{AC_NDM}]
B	Average [UP_{BA1}-UP_{BA_NDM}]	Average [UP_{BB1}-UP_{BB_NDM}]	Average [UP_{BC1}-UP_{BC_NDM}]
C	Average [UP_{CA1}-UP_{CA_NDM}]	Average [UP_{CB1}-UP_{CB_NDM}]	Average [UP_{CC1}-UP_{CC_NDM}]

Where UP_1-is the score of a pair-wise comparison (AA-AC, BA-BC & CA-CC) of a decision maker within a group say the Urban Planner. This process is repeated to generate the scores for the judgement matrix for the engineers (UE) and socio-economists (USE).

Determination of priority vector

The priority vector is determined by synthesizing the priority matrix. This is done by dividing each element of the judgement matrix by the total of its column. For example, the value of 0.667 in Table 3-5 is obtained by dividing 1 (from Table 3-3) by 1.5, the sum of column one in Table 3-3 (1+0.33+.017). The priority vector in Table 3-5 is obtained by determining the row averages. For example, the priority of indicator A with respect to decision maker DM1 in Table 3-5 is calculated by dividing the sum of the rows by the number of indicators (columns) (0.667+0.714+0.5)/3 to obtain 0.627. The priority vector for DM1 indicated in Table 3-4 is given by

$$\begin{bmatrix} 0.627 \\ 0.292 \\ 0.081 \end{bmatrix} \qquad [3\text{-}6]$$

Table 3-5: Priority vector for SII indicators

DM1	A	B	C	Priority Vector
A	0.667	0.714	0.500	0.627
B	0.220	0.238	0.417	0.292
C	0.113	0.048	0.083	0.081

Checking consistence of the judgement matrix

Finally the consistence of the decision maker's comparisons is computed based on Equation 3.2 & 3.3 using the following four steps:

(a) Determination of the weighted sum vector from:[Judgement matrix] x [Priority vector]

$$\begin{bmatrix} 1 & 3 & 6 \\ 0.33 & 1 & 5 \\ 0.17 & 0.2 & 1 \end{bmatrix} \begin{bmatrix} 0.627 \\ 0.292 \\ 0.081 \end{bmatrix} = \begin{bmatrix} 1.9903 \\ 0.9056 \\ 0.2463 \end{bmatrix} \qquad [3\text{-}7]$$

Weighted sum vector

(b) Determination of the consistence vector from: $\dfrac{\text{i}^{\text{th}}\text{ entry in weighted sum vector}}{\text{i}^{\text{th}}\text{ entry in priority vector}}$

$$= \begin{bmatrix} 1.9903/0.627 \\ 0.9056/0.292 \\ 0.2463/0.081 \end{bmatrix} = \begin{bmatrix} 3.174 \\ 3.106 \\ 3.025 \end{bmatrix} \qquad [3\text{-}8]$$

(c) Determination of the CI using equation 3.2

$$\bar{\lambda}_{\max} = \frac{3.174+3.106+3.025}{3} = 3.102 \qquad [3\text{-}9]$$

$$CI = \frac{3.102-3}{(3-1)} = 0.0509 \qquad [3\text{-}10]$$

(d) Determine the consistence ratio from $CR_{JM} = CI / R_{CI} * 100$

Where RCI for n=3 is 0.58 based on table 3.2

$$CR_{JM} = \frac{0.0509}{0.58} x100 = 8.8\%$$

$CR_{JM}<10\%$. Hence, the consistence of the decision maker DM1 is OK

3.4 Framework for development of SII

In this section, a framework is presented that enables the analysis of SEI due to UWDS transition based on a single composite SII. The proposed SII framework shown in Figure 3-1is based on modifications of the original Simple Multi-Attribute Rating Technique (SMART) steps presented by Goodwin and Wright (2004). The modification was aimed at tailoring the technique to the SII problem. SMART was first introduced in 1971 and has undergone various modifications (Edwards and Barron 1994). The technique is used because of its simplicity in elicitation of stakeholder preferences and the analysis of responses (Kabli 2009). The proposed SII framework involves three phases. The first phase is the problem structuring and inception phase. The second is the design phase and the third is the evaluation and analysis phase. Details of the steps in each phase and implementation of the proposed framework within the SII development context are elaborated:

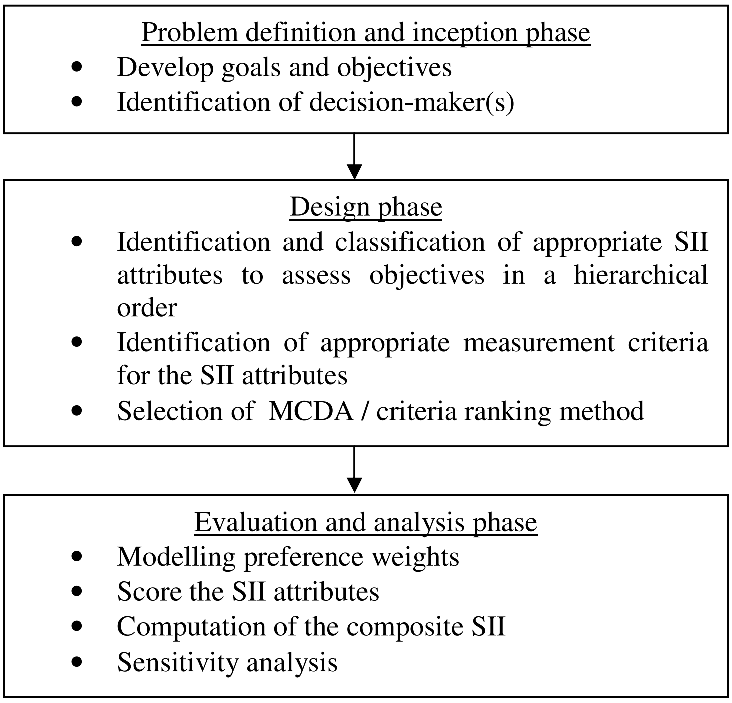


Figure 3-1: Framework for development of SII

3.4.1 Problem definition and inception phase

The aim of the problem definition and inception phase is to develop a clear problem statement for development of the indicator agreed upon by all decision-makers. Identification of a concise problem statement requires identification of the root causes through analysis of cause-effect relationships between the transitions of UWDS and the impacts in an urban area. The goals and objectives are developed from the problem statement and from the cause-effect relationship and should include SII dimensions such as the UC, UI and SE aspects. Normally, these objectives are conflicting.

The next step after outlining the aims and objectives of the SII development is the identification of the stakeholders to participate in the decision process. In this chapter, stakeholders and decision-makers are used inter-alia to refer to people with a vested interest in the impacts and consequences of the UWDS transition. Stakeholders can participate in the decision making process either as individuals or a group. However, care should be taken to ensure that the identified decision-makers have the appropriate knowledge and experience in their respective areas of expertise. In most studies, decision making in an environment with conflicting criteria; is made using groups (Khatri et al. 2011). Groups have the ability to improve the quality and acceptability of the result. For the same reasons, group decision making is adopted in this study although it has its drawbacks (Kabli 2009; Mutikanga et al. 2011). The ultimate goal of the problem definition and inception phase is to develop clear and concise aims and objectives of the SII and to identify appropriate stakeholders to participate in the decision process.

3.4.2 Design phase

The design stage involves the identification and classification of SII attributes to assess the objectives, identification of appropriate measurement methods for criteria and selection of appropriate MCDA (criteria ranking method). The first stage in this phase involves identification of attributes for assessing SII and arranging them in a hierarchical order. The selection of attributes to assess the SII is derived from the described objectives outlined in Section 3.4.1. The attributes should be able to measure the extent to which goals and objectives of the SII are achieved. These should be distinguishable, measurable and covering all aspects of the SII objectives stating their value and merit in the decision process (Mutikanga 2011). The attributes which should neither be neither too many nor too few. That is, a maximum of nine according to

Mutikanga (2011) and between six and twenty based on the UK Department of Communities and Local Government (UKDCLG) UKDCLG (2009).

Attributes to access SII are identified based on analysis of cause-effect relationships between UWDS transitions and the impacts in an urban area. DPSIR developed by OECD (1993) is an example of a framework developed to aid the analysis of cause-effect relationships between man and the environment. Details of this framework and its pros and cons have been elaborated in Section 2.8 and 2.8.1. Based on the framework, UWDS transitions affect urban infrastructure, urban form and the socio-economic characteristics of the inhabitants of the urban area. However, these attributes are most of the time conflicting (Mutikanga 2011). The DPSIR framework reveals the UWDS transition impact areas, categories and attributes to be used to assess SII. The attributes can then be identified from available literature (Bowen and Riley 2003; Brent and Labuschagne 2006; Carden et al. 2009).

Attributes can be numerous and therefore require simplification into decision elements and structuring into different levels of a hierarchy (Saaty 2008). The goal is placed at the first level of the hierarchy while the SII categories are identified to contribute to the goal and are placed at the second level. These SII categories represent the boarder impact dimensions and indicators to reflect different aspects of the SII urban area by which SII will be measured. Finally, a number of sub-criteria are defined for each category and are placed at the third level. The method used to characterize and classify SII is based on the approach used by Khatri et al (2011) for computation of the performance index of UIS. The attributes can then be identified from available literature (Bowen and Riley 2003; Brent and Labuschagne 2006; Carden et al. 2009)

The next step after identification and structuring the SII attributes in a hierarchical order is the identification of appropriate measurement methods and criteria to assess the objectives. The choice of the appropriate measurement criteria for the SII attributes is based on the identified attributes (dimensions, criteria and indicators). The measurement criteria should be able to provide an appropriate scale by which the attributes can be measured. The SII attributes can be either of a quantitative or qualitative nature while others may be on limited or missing data. The quantitative data can be based on the units of the data drawn from secondary data. On the other hand, the qualitative category can be based on the value function technique which uses the decision-makers rank of the preference of an option or indicator. The qualitative category can also be based on the performance scales technique which scores attribute based on a scale such as the use of linguistic variables with 5 representing a very high impact and 1 (very low impact). The identified measurements criteria should be able to measure all types of attributes both qualitative and quantitative.

The last step in this phase is the selection of an appropriate MCDA technique. There are many MCDA techniques and these together with their pros and cons have been described in Section 3.2. Selecting a suitable MCDA technique is not an easy task (Abrishamch et al. 2005) . The guidelines on how to select an appropriate MCDA method can be found in Kabli (2009). These also depend on the characteristics of the problem and the experience and preference of the decision-maker and analyst. The method which is easier to use and more familiar to the decion-makers is chosen.

3.4.3 Evaluation and analysis phase

The final phase concentrates on the evaluation (scoring each attribute, assigning weights) of the attributes in the hierarchy identified in Section 3.4.2. It involves the following steps Modelling preference weights, scoring the SII attributes, Computation of the composite SII and sensitivity analysis.

In the first step, weights are assigned to the attributes by the decision makers as a true representation of their significance in assessing SII. The weight allocation process is a subjective exercise undertaken by the identified stakeholders. It is therefore important that the weights for the attributes are assigned based on the approaches that are easy to use and that yield results which are acceptable to decision-makers such as the AHP (Saaty 2008). There are two approaches for weighting attributes and these are equal weight approach and rank-order approach. The equal weight approach is preferred because it requires minimal input from the decision maker. However, the critics of this approach say that the assumption that all attributes have equal weights is not consistent with practice. To circumvent this limitation, researchers have proposed the rank order method that is based on the assumption that weights are not equal and their sum is equal to one. In this study, we apply the AHP technique to assign weights (Saaty 2008). The pros and cons for this approach and why it has been selected have been elaborated in Section 3.3.

The next step is the scoring the SII attributes identified in Section 3.4.2. Scoring is aimed at developing an evaluation matrix (EM). Each score assigned by the decision maker or obtained from literature represents an assessment of the attribute with respect to causing an impact in the urban area. The exercise of scoring the attributes is undertaken by identified decision makers who have good knowledge about the attribute being measured. The scores capture both qualitative and quantitative data types. Quantitative scores can be derived from secondary sources, such as the Uganda Demographic and Health Survey (UDHS) reports while the qualitative scores are enlisted from primary sources such as questionnaires sent to decision-makers requesting them to rank criteria and to score attributes based on conversion of linguistic terms into quantitative scales.

Sensitivity analysis is a tool used to assess whether changes in the priorities of the attributes could influence the outcome of the indicator. It is used to examine how robust the SII is to the change in the weight of the dimensions, criteria and indicators (Goodwin & Wright 2004). This is because there is a possibility that the composite SII could change with change in weights of the attributes. While sensitivity analysis can be applied to weights, its application to scores is elusive as it requires rescoring by the decision makers which is time consuming.

3.5 Case study -Application of the developed SII framework

Firstly, how the developed framework can be applied to the problem of assessing SEI due to the transition of UWDS in Iganga Water and Sewerage Service Area (I-UWDS) and Kampala Urban Water Distribution System (KUWDS); part of the branches in the National Water and Sewerage Corporation (NWSC) service area is considered. KUWDS is the largest branch constituting about 70% of NWSC; serving Kampala the capital city of Uganda. The service area has experienced many SEI as the UWDS transitioned from a system designed to serve a population of just 2850 in 1930 to the present UWDS that covers a population of about 1.5 million people.

On the other hand, I-UWDS located in Iganga Municipal Council lies in the east and northeast of Uganda about 120 km from Kampala. I-UWDS has transitioned in tandem with the rapid urbanisation and population growth in the area which has grown from 6,000 to 100,000 between 1969 and 2012 (BKS Global and Kagga and Partners 2012; Habitant Consultants 1994; UBOS 2002).

These case study areas represent the SEI faced by an emerging area (I-UWDS) and a developed area (KUWDS). Moreover, these impacts are anticipated to increase exponentially in the future. However, the challenge is how to compute the zones with the highest anticipated impacts due to UWDS transitions. The case studies are used to demonstrate the robustness of the framework shown in Figure 3-1.

Problem definition and inception phase: Based on the aforementioned case study information, the problem statement was to identify and prioritise SEI in the different transition zones of Iganga and Kampala. The goal of this study is to minimise UWDS transition impact costs. Based on the problem statement and the goal, the established objectives were the minimisation of UC, UI and SE due to UWDS transitions.

Identification of decision-maker(s): Three classes of professionals that work with the different categories of the SII was identified.the engineer-to take care of infrastructure impacts, the planner to take care of impacts on the urban form and the socio-economists to take care of impacts on the communities and their livelihoods. These experts were drawn from the different institutions that face or are impacted by the transition of UWDS, including municipal and city council authorities, NWSC staff, District officials and Central government authorities. For Iganga, the experts included the District Water Officer with ten years of experience in the area, he was also the in charge of the Iganga Water board before it was upgraded and transferred to NWSC, the area manager of Iganga Water who is in charge of the management of the water utility, the Municipal Engineer who is in charge of drainage and urban infrastructure and has seen the town transition to a municipal council and community health and social mobilisers living in the study area. For Kampala, the experts include: the water loss control manager and former general manager of Kampala Water, with 15 years of experience in the area principal engineer water loss control and Water network; and manager decision support systems and GIS.

Design phase

Identification and classification of appropriate SII attributes to assess objectives in a hierarchical order: The goal which is to obtain an UWDS transition SII is placed at first level as shown in Figure 3-2. Three dimensions / criteria namely UC, UI and SE identified to achieve the goal are positioned at the second level (Figure 3-2). The first category at the second level, UC is considered because it captures the impact of the UWDS transition on the urban form. This impact on urban form depends on the type of settlement, settlement structure and whether it is planned or unplanned. This category is based on the assumption that the position and level of development of a dwelling unit is the key attribute by which urban form is impacted by an UWDS transition. Five sub criteria include level of urban development, type of roofing material, material for walls, floor material, and percentage of built up area are identified to contribute to UC .These form the third level in the hierarchy as shown in Figure 3-2. Measurement of attributes in this category are based on both crisp (obtained from secondary) data and linguistic scales obtained from experts identified in the first phase.

The second category at the second level of UI is equally vital. It focuses on the anticipated impact on the existing infrastructure. There are four urban infrastructure systems associated with UI. These are the sanitation/sewerage system, the urban drainage system, UWDS and the road infrastructure system which are placed at the third level in the hierarchy. Because of limited quantitative data, measurement of sub criteria in this category is based on linguistic variables with 5 representing a very high impact and 1 (very low impact). The measurement of sub criteria was also based on scoring by experts identified in the first phase.

Finally is the SE: This is the last category for the second level (Figure 3-2) selected to take care of the metrics on the well-being and standard of living where the UWDS transitions are being implemented. Three sub criteria are presented. They include wealth index for low income communities or the human development index population density and the local economy positioned at the third level Figure 3-2 are identified to contribute to SE.

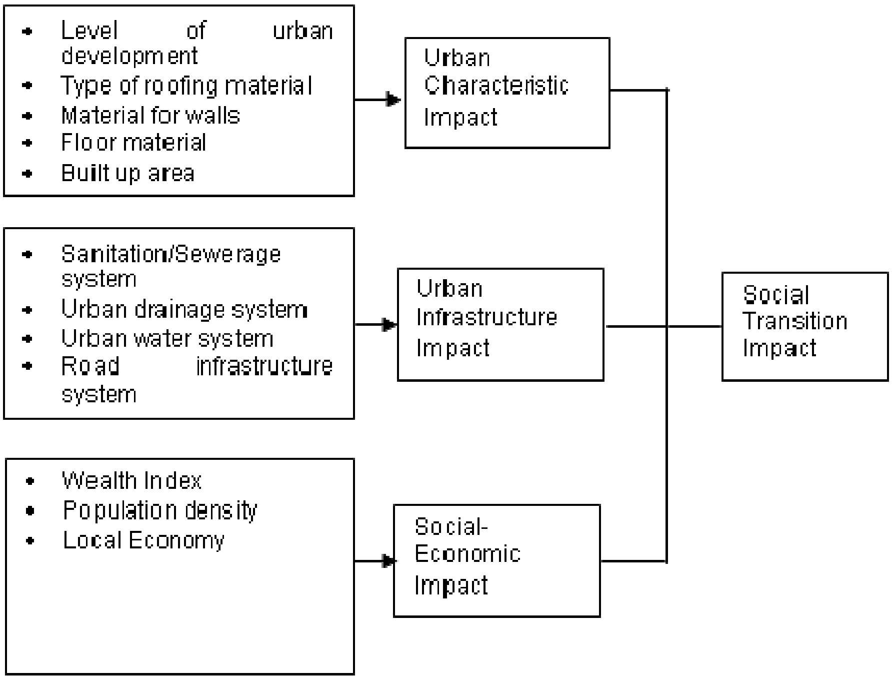


Figure 3-2: Hierarchical structure of the SII

Identification of appropriate measurement criteria for the SII attributes: The measurement criteria shown in Table 3-6 were generated based on secondary data sourced from the 1995, 2000 and 2006 Uganda Demographic Health Survey (UDHS). The criteria selected were those deemed suitable to assess SEI of the SII categories with respect to achieving the desired objectives and goals. In addition the criteria were selected because they had readily available data with respect to the criteria being assessed.

Table 3-6: Measurement criteria for SII attributes

Criteria	Sub Criteria	Assessment score guideline
Urban Characteristic Impact [UC]	Level of urban development	1-Very low devpt;2-Low devpt;3-Average devpt;4-High devpt;5-Very High development
	Type of Roofing Material	1-Natural/Rudimentary;2-Iron Sheets;3-Tiles/Asbestos
	Material for Walls	1-Natural/Rudimentary;2-Iron Sheets;3-Burnt Clay/Cement
	Floor material	1-Natural/Earth;2-Cement;3-Finished/Tiles
	% Built up area	1-Very low; 2-Low; 3-Average;4-High;5-Very High
Urban Infrastructure Impact [UI]	Sanitation/Sewerage system	Mode % of toilet facility:1-No, 2-Pitlatrine, 3-VIP,4 Flush
	Urban Drainage/Sewerage	1-No drains; 2-unlined drains;3-Lined drains
	Urban Water System	Mode: water source option: 1-unimproved;2-improved;3 yard taps;4-house connection
	Roads	Mode/largest type of road network: 1-Earth;2-Gravel;3 Tarmac
Socio-economic Impact [SE]	Wealth Index	Mode largest % wealth index: 1-Poorest;2-Poorer;3-Middle;4-Richer;5-Richest
	Population density	Actual population density
	Local Economy	1-Very low;2-Low;3-Average;4-High;5-Very High

Selection of MCDA / criteria ranking method: The attributed weighting method selected was the AHP. The pros and cons of this method and why it was selected have been discussed in Section 3.2 and 3.3

Evaluation and analysis phase

Modelling preference weights: The preference weights in this case study were modelled using the AHP technique which involved three steps described in Section 3.3 and the simplified example presented in Section 3.3.1. That is, construction of judgement matrix based on pair-wise comparison, determination of priority vector and examination of the consistence vector. The Construction of judgement matrix involved undertaking a questionnaire survey that required stakeholders to undertake a pair-wise comparison between the dimensions, criteria and indicators using the Saaty scale. Based on the pair-wise comparisons, weights for the SII attributes were generated. The survey was carried out by sending questionnaires to the respondent by email while some were distributed manually. The response group and the response rates are presented in Table 3-7 and the questionnaire is shown in the Appendix-A-2. The identified experts are decision-maker(s) identified in the Section 3.5. During this exercise weights were assigned for each of the dimensions, criteria and indicators to reflect their relative rank with respect to cause impacts in an urban area due to UWDS transitions. The results of the AHP process are shown in the judgment matrix and priority vector for the criteria and sub-criteria in Table 3-8 and Appendix A-1. This table indicates that the urban infrastructure indicator, the urban characteristic indicator and the socio-economic indicators are equally important. The priority vector was obtained using the geometric mean method as elaborated in the framework development. For simplicity, equal weights; that is, $W_{engineer} = W_{planner} = W_{socio-economist} = 0.3333$ of the decision maker were used in the study. The scores included in the judgement matrix were obtained from the mean of the priority scores of the usable questionnaires for each group of decision makers.

Table 3-7: Questionnaire Response rate

Subject Experts	Initial Questionnaires	Usable questionnaires	Response Rate
Planner	9	9	100%
Engineer	45	15	33%
Socio-Economist	15	8	53%
Total	69	32	46%

Table 3-8: Judgement matrix for the criteria level

		Scores												
Subject Experts	Criteria Level	Urban Characteristic Impact	Urban Infrastructure Impact	Socio-economic Impact	Urban Characteristic Impact	Urban Infrastructure Impact	Socio-economic Impact	Urban Characteristic Impact	Urban Infrastructure Impact	Socio-economic Impact	Urban Characteristic Impact	Urban Infrastructure Impact	Socio-economic Impact	Priority Vector
Planners	Urban Characteristic Impact	1.00	3.0	6.00										0.63
	Urban Infrastructure Impact	0.33	1.00	5.00										0.29
	Socio-economic Impact	0.17	0.2	1.00										0.08
Engineers	Urban Characteristic Impact				1.00	0.33	7							0.29
	Urban Infrastructure Impact				3.00	1.00	9.00							0.65
	Socio-economic Impact				0.14	0.11	1.00							0.06
Socio-Economist	Urban Characteristic Impact							1.00	6.00	0.33				0.30
	Urban Infrastructure Impact							1/6	1.00	1/7				0.07
	Socio-economic Impact							3.00	7.00	1.00				0.63
Over all	Urban Characteristic Impact										1.00	3.11	4.44	0.41
	Urban Infrastructure Impact										1.17	1.00	4.71	0.32
	Socio-economic Impact										1.10	2.44	1.00	0.27

The judgement matrix for the sub criteria level can be found in the Appendix A-1. The priority vector was established following the process described in Section 3.3 and the simplified example 0(ii). The scores in the judgement matrix were obtained from the mean of the priority scores of decision makers. The results for application of the procedure in the case study can be found in Table 3-9 (Kampala) and Table 3-10 (Iganga).

Table 3-9: SII Scores for the Parishes in Rubaga Division in Kampala

RUBAGA DIVISION-KAMPALA CITY COUNCIL

Criteria	Sub Criteria	Field assessment Score							Normalisation								Normalisation Weights						
		Zone 1-Mityana Road	Zone 2-Kasubi,Lungujja, Lubya, Nakulabye	Zone 3-Nansana , Wakiso	Zone 4-Busega, Mutundwe, Kyengera	Zone 5-, Namirembe,Rubaga	Zone 6-Ndeeba Natete	Zone 7-Najanankumbi I I & II-Kabowa	Zone 1-Mityana Road	Zone 2-Kasubi,Lungujja, Lubya, Nakulabye	Zone 3-Nansana , Wakiso	Zone 4-Busega, Mutundwe, Kyengera	Zone 5-, Namirembe,Rubaga	Zone 6-Ndeeba Natete	Zone 7-Najanankumbi I I & II-Kabowa	Weights	Zone 1-Mityana Road	Zone 2-Kasubi,Lungujja, Lubya, Nakulabye	Zone 3-Nansana , Wakiso	Zone 4-Busega, Mutundwe, Kyengera	Zone 5-, Namirembe,Rubaga	Zone 6-Ndeeba Natete	Zone 7-Najanankumbi I I & II-Kabowa
Urban Characteristic Impact [UC]	Level of urban development [SC-1]	1	3	2	4	5	5	2	0.20	0.60	0.40	0.80	1.00	1.00	0.40	0.14	0.03	0.08	0.05	0.11	0.14	0.14	0.05
	Type of Roofing Material [SC-2]	1	2	3	4	3	2	2	0.25	0.50	0.75	1.00	0.75	0.50	0.50	0.13	0.03	0.06	0.10	0.13	0.10	0.06	0.06
	Material for Walls [SC-3]	1	2	2	3	3	4	3	0.25	0.50	0.50	0.75	0.75	1.00	0.75	0.07	0.02	0.04	0.04	0.06	0.06	0.07	0.06
	Floor material [SC-4]	2	2	2	3	3	3	2	0.67	0.67	0.67	1.00	1.00	1.00	0.67	0.03	0.02	0.02	0.02	0.03	0.03	0.03	0.02
	% Built up area [1-low 5-High] [SC-5]	2	5	2	3	4	4	3	0.40	1.00	0.40	0.60	0.80	0.80	0.60	0.03	0.01	0.03	0.01	0.02	0.03	0.03	0.02
Urban Infrastructure Impact [UI]	Sanitation/Sewerage system [SC-6]	2	3	2	3	4	4	3	0.50	0.75	0.50	0.75	1.00	1.00	0.75	0.14	0.07	0.11	0.07	0.11	0.14	0.14	0.11
	Urban darinage/Sewerage [SC-7]	2	2	1	3	3	2	2	0.67	0.67	0.33	1.00	1.00	0.67	0.67	0.05	0.04	0.04	0.02	0.05	0.05	0.04	0.04
	Urban Water System [SC-8]	3	3	2	3	4	3	4	0.75	0.75	0.50	0.75	1.00	0.75	1.00	0.11	0.09	0.09	0.06	0.09	0.11	0.09	0.11
	Roads [SC-9]	2	2	1	2	3	3	2	0.67	0.67	0.33	0.67	1.00	1.00	0.67	0.02	0.01	0.01	0.01	0.01	0.02	0.02	0.01
Socio-economic Impact [SE]	Wealth Index [SC-10]	1	2	4	3	5	4	4	0.20	0.40	0.80	0.60	1.00	0.80	0.80	0.17	0.03	0.07	0.14	0.10	0.17	0.14	0.14
	Population density [SC-11]	2	5	3	3	3	5	3	0.40	1.00	0.60	0.60	0.60	1.00	0.60	0.08	0.03	0.08	0.05	0.05	0.05	0.08	0.05
	Local Economy [SC-12]	2	3	2	3	4	5	3	0.40	0.60	0.40	0.60	0.80	1.00	0.60	0.02	0.01	0.01	0.01	0.01	0.01	0.02	0.01
					SII												0.39	0.64	0.57	0.76	0.91	0.85	0.68

Table 3-10: SII Scores for Parishes located in Iganga

		IGANGA MUNICIPAL COUNCIL															
		Field assessment Score					Normalization						Normalized Weights				
Criteria	Sub Criteria	Bugumba-Northern Zone	Western-jinja Rd-CMS	Kasokoso	Tororo Rd/ Eastern Zone	Nkono I & II	Bugumba-Northern Zone	Western-jinja Rd-CMS	Kasokoso	Tororo Rd/ Eastern Zone	Nkono I & II	Weights	Bugumba-Northern Zone	Western-jinja Rd-CMS	Kasokoso	Tororo Rd/ Eastern Zone	Nkono I & II
Urban Characteristic Impact [UC]	Level of urban development [SC-1]	2	1	5	3	2	0.40	0.20	1.00	0.60	0.40	0.14	0.05	0.03	0.14	0.08	0.05
	Type of Roofing Material [SC-2]	2	1	3	3	1	0.67	0.33	1.00	1.00	0.33	0.13	0.09	0.05	0.14	0.14	0.05
	Material for Walls [SC-3]	2	1	3	3	2	0.67	0.33	1.00	1.00	0.67	0.07	0.09	0.05	0.14	0.14	0.09
	Floor material [SC-4]	2	2	3	2	2	0.67	0.67	1.00	0.67	0.67	0.03	0.09	0.09	0.14	0.09	0.09
	% Built up area [1-low 5-High] [SC-5]	4	1	5	3	2	0.80	0.20	1.00	0.60	0.40	0.03	0.11	0.03	0.14	0.08	0.05
Urban Infrastructure Impact [UI]	Sanitation/Sewerage system [SC-6]	2	2	3	4	2	0.50	0.50	0.75	1.00	0.50	0.14	0.07	0.07	0.10	0.14	0.07
	Urban darinage/Sewerage [SC-7]	1	1	3	2	1	0.33	0.33	1.00	0.67	0.33	0.05	0.05	0.05	0.14	0.09	0.05
	Urban Water System [SC-8]	3	2	3	4	2	0.75	0.50	0.75	1.00	0.50	0.11	0.10	0.07	0.10	0.14	0.07
	Roads [SC-9]	2	2	3	2	1	0.67	0.67	1.00	0.67	0.33	0.02	0.09	0.09	0.14	0.09	0.05
Socio-economic Impact [SE]	Wealth Index [SC-10]	2	1	3	4	2	0.50	0.25	0.75	1.00	0.50	0.17	0.07	0.03	0.10	0.14	0.07
	Population density [SC-11]	0.815	0.831	1	1	0.984	0.81	0.83	1.00	1.00	0.98	0.08	0.11	0.11	0.14	0.14	0.13
	Local Economy	2	2	5	2	2	0.40	0.40	1.00	0.40	0.40	0.02	0.05	0.05	0.14	0.05	0.05
		SII											0.97	0.70	1.52	1.30	0.81

To ensure that the weights are consistent, the consistence ratio was computed using Equations 3-2 and Equation 3-3. For the case study, the consistence ratio for the criteria and sub criteria are presented in Table 3-11 and these certify the condition. Hence, the judgement matrix is consistent.

Table 3-11: Consistence ratios for the criteria

Subject Experts	Criteria Level	Priority Vector	Weighted Sum Vector	Consistence vector	Consistence Index	Consistence Ratio
Planners	UC	0.63	1.99	3.17	0.05	0.08
	UI	0.29	0.90	3.10	0.05	
	SE	0.08	0.24	3.02	0.05	
Engineers	UC	0.29	0.91	3.08	0.04	0.07
	UI	0.65	2.04	3.15	0.04	
	SE	0.06	0.17	3.01	0.04	
Socio-Economist	UC	0.30	0.93	3.10	0.05	0.09
	UI	0.07	0.21	3.02	0.05	
	SE	0.63	2.01	3.18	0.05	
Over all	UC	0.41	2.61	6.43	0.04	0.07
	UI	0.32	2.07	6.37	0.04	
	SE	0.27	1.51	5.60	0.04	

The consistence ratios for the sub criteria can be found in the Appendix A-1. Both consistence levels were within acceptable limits. This means that the opinions for the experts were consistent.

Scoring attributes: The quantitative data to score the criteria was obtained from secondary sources. That is UDHS report, the district and council development plans and from discussions with key experts. On the other hand, qualitative scoring of some criteria was implemented using a linguistic scale. That is 1 (poor) to 5 (very good). These were obtained by a second set of questionnaires sent out to experts and stakeholders. The individual and group decision scores are shown in Table 3-9 (Kampala) and Table 3-10 (Iganga).

Computation of the composite SII: The composite SII was computed from the product of normalised EM and the weights representing the relative importance of the attributes being evaluated. The results for the computation of the composite SII for the different UWDS transition zones are shown in Table 3-9 (Kampala) and Table 3-10 (Iganga). The outcome for these SII for the different zones are applied to the pipes located in the respective transition zones.

Sensitivity analysis: To test the sensitivity of the SII, the above procedure was repeated but this time with equal weights for all criteria and sub-criteria. The results show that there is little deviation from the previous analysis results. The results for the sensitivity analysis are shown in Table 3-12

Table 3-12: Sensitivity analysis for Iganga and Rubaga weights

	RUBAGA							IGANGA				
Description of UWDS transition zone	Zone 1-Mityana Road	Zone 2-Kasubi,Lungujja, Lubya, Nakulabye	Zone 3-Nansana , Wakiso	Zone 4-Busega, Mutundwe, Kyengera	Zone 5-, Namirembe,Rubaga	Zone 6-Ndeeba Natete	Zone 7-Najanankumbi I I & II-Kabowa	Zone 1-Kasubi,Lungujja, Lubya, Nakulabye	Zone 2-Nansana , Wakiso	Zone 3-Busega, Mutundwe, Kyengera	Zone 4-, Namirembe,Rubaga	Zone 5-Ndeeba Natete
SII based on AHP weights	0.39	0.64	0.57	0.76	0.91	0.85	0.68	0.64	0.46	1.00	0.85	0.54
SII based on equal weights	0.45	0.68	0.52	0.76	0.89	0.88	0.67	0.60	0.43	0.94	0.80	0.50
Standard deviation	0.04	0.03	0.04	0.00	0.01	0.02	0.01	0.03	0.02	0.04	0.04	0.02

The results show that SIIs are not as such sensitive to the weights of the assigned performance. This is because the many criteria means that the equal weights do not vary much from those allocated to each criterion.

3.6 Results discussion

The SII of the UWDS transition Zones for Iganga and Kampala were assessed using the developed approach so as to identify the zones that have the least SII on the future transitionability of the UWDS. Based on the results, SII for the five zones in Iganga Case Study Area and the seven zones in Kampala Cases Study Area were computed. The UWDS transition zone with a lowest SII (0.39) is Mityana Road and that with the highest SII (0.91) for Kampala and Kasokoso 1 & II (0.7) and Tororo road- the Eastern zone (1.52) for Iganga Case Study respectively. The general trend is that SII for the developed zones in Iganga and Kampala was higher than that in the least developed areas. This means that there is greater potential to transition an UWDS in zones with lower SII because of minimal impacts. This is because these areas are 'green fields' that do not have legacy UWDS infrastructure and socio-economic characteristics that act as barriers to the transition process.

The approach for computation of SII that is based around MCDT for the development of indicators and the AHP for the computation of the weights is suitable for assessment of socio-economic impacts due to UWDS transitions. However, there exists shortcomings that may have influenced the results of the model such as typology of indicators used as these have been based on secondary data (UDHS 2000-2006) and indicators from literature, the aggregation of dimensions and indicators using weights which depend on the weighting approach used, data quality and the methodology of scoring the dimensions and criteria using qualitative approaches may have been prone to bias.

The other limitation of the SII approach is that while it is suitable in data scarce scenarios, it is criticized for being subjective. Nevertheless, integration of UI, UC, and SE dimensions yields more acceptable results than depending on a single indicator.

CHAPTER FOUR

MODELLING SOCIO-TECHNICAL TRANSITIONS OF UWDS

4. Chapter overview

Although researchers have long analysed transitions in urban water management, the application of quantitative approaches to predict switches between options has not been addressed and the socio-economic characteristics associated with transitions between UWDS options remain unclear (Brown et al. 2009; Brugge et al. 2005; Schot and Rip 1997). To address the knowledge gaps, this study uses secondary data from the Uganda Demographic and Health Survey data on households for the period 1995, 2000 and 2005 and the Multinomial Logistic (MNL) regression to examine the association of household socio-economic and demographic characteristics and the transition between UWDS option. To identify the most significant socio-economic and demographic characteristics that is related to UWDS.

The results of the association between UWDS options and the transition between UWDS choices and socio-economic characteristics such as residence, education level, wealth status, age of household head, housing characteristics, type of toilet facility, floor material, wall material and roof material are presented. These are used characterise house hold socio-economic attributes. The empirical results indicate that connection to electricity and type of toilet facility is the household socio-economic characteristics that are associated with the transition between UWDS options. The understanding of these relationships enables engineers and planners to identify appropriate socio-economic characteristics to the uptake, efficiency and costs for UWDS transitions. Planners and engineers in the urban water sector should adopt an integrated approach to increase the uptake and overcome the barriers to UWDS transitions.

This chapter is structured in seven sections. Section 4.1 introduces and gives a brief overview of the study undertaken. Section 4.2 reviews the perspectives of the global transition in UWDS options. Section 4.3 describes the data, variables and methodology used for data analysis. The Conceptual and empirical model for modelling of socio-technical transitions of UWDS is presented in Section 4.4. Section 4.5 presents and analyses the results of the empirical model. Finally, Section 4.6 discusses the results of the study.

4.1 Introduction

Technological transitions are a socio-technical problem (Brown and Clarke 2007; Brown et al. 2008; Foxon et al. 2008; Krueger 2002; Totti 2008). Although the interactions between the different components of the socio-technical system have recently been analysed, the quantitative analysis of the relationship between socio-economic characteristics and transitions remains a challenging problem to undertake particularly for UWDS. Recently, the multi-level model (Rip and Kemp 1998) has been used to understand the interactions between the different components of the socio-technical system. However, it is criticized for being descriptive and not supported with quantitative data (Brugge et al. 2005; Schot and Rip 1997).

Statistical modelling remains the most widely applied approach for the analysis of the relationship between socio-economic attributes and technological adoption or diffusion. For example, internet (Thong 1999; Wahid 2007) in developing countries (Besley and Case 1993), households (Brown and Venkatesh 2005) and biogas (Mwirigi et al. 2009; Walekhwa et al. 2009). However, these studies focused on dichotomous outcomes based on binomial logistic regression (BNL) to predict association with socio-economic characteristics; - a model that considers more than two outcomes is lacking. Moreover, existing studies are in other fields and the association between socio-economic characteristics and transitions between UWDS options remain unclear. Modelling the association based on a transition (1) and no transition (0) is impractical particularly for UWDS where technological options are often numerous and nonlinear.

To deal with these knowledge gaps, the study aims to apply Multinomial Logistic Regression (MNL) to model the relationship between socio-economic and demographic characteristics and the transition in UWDS options. Understanding the relationships between socio-economic characteristics and the transition of a technology will enable identification of the most significant factors to be modified so as to increase speed in the transition of UWDS options.

4.2 Global Transition in UWDS Options

Over the last three decades there have been two major global efforts to increase access to safe water and sanitation but the uptake and transition of these technologies has been very low. The efforts include the international decade of Water Supply and Sanitation and the Millennium Development Goals (MDG, 2005-2015). The first initiative began in 1990 and aimed to provide safe water and sanitation for all. By the end of the project, only 1 billion people had access to water. Whereas significant progress was made in constructing safe water technologies thereby increasing access to 1 billion people, the uptake of these technologies was very low. This was portrayed as continued use of traditional sources and the improper use of the existing ones leading to breakdown and abandonment of the technologies. In terms of technological adaptation, the project was criticized for inadequate community education, lack of consideration of the perceptions of the users and the socio-demographic characteristics. Whereas some technologies were acceptable in particular areas, some were not in the same areas. Despite these predicaments, the second initiative, the international decade for action-Water for life, emphasized the models of community participation and the innovation diffusion model. As such, the project emphasized bottom up planning, meaningful involvement and the engagement of the communities in developing sources. According to the JMP report (UNICEF and WHO 2012), this approach has yielded positive results. However, there is a need to consider the third model which understands the interaction between the socio-economic and demographic characteristics and the transition in UWDS options. The trends in the transition UWDS options use are presented in the Figure 4-1. The greatest transition required in the adoption of UWDS options are in sub Saharan Africa.

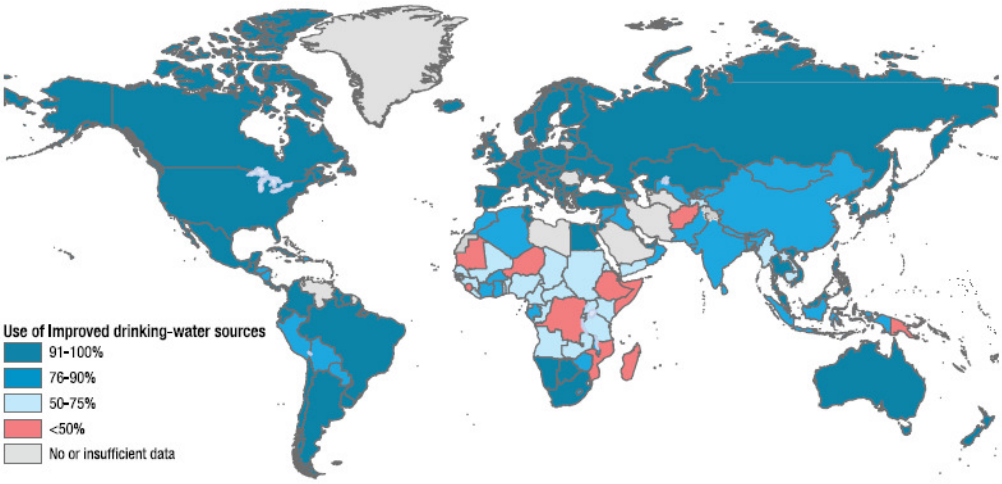


Figure 4-1: Worldwide use of improved drinking water sources in 2008 (UNICEF and WHO 2012)

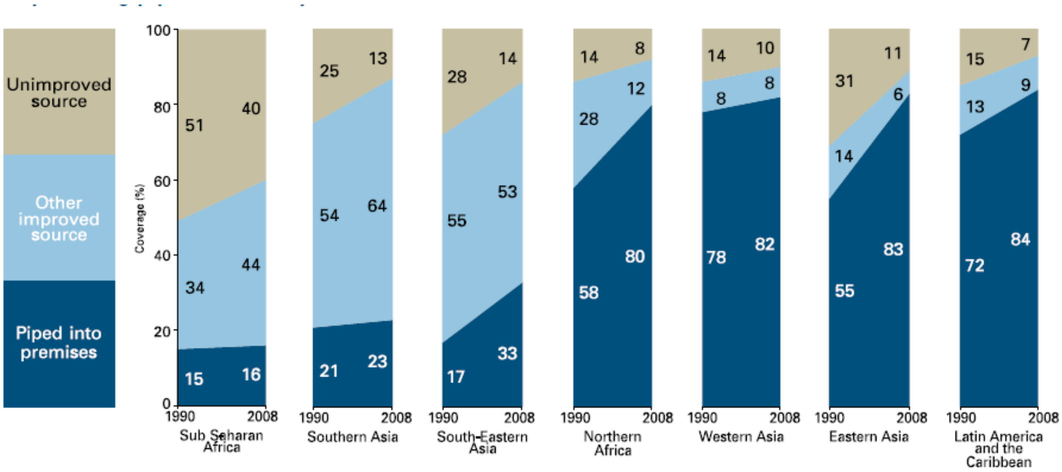


Figure 4-2: Proportion of the population with house connections visa vis other drinking water sources (UNICEF and WHO 2012)

While significant progress has been made in increasing water coverage, limited progress has been made with respect to achieving a transition in the proportion of people using point water sources. A more specific example is found in Kampala the capital city of Uganda, where only 8% of the population actually has a domestic house connection as compared to purported 70% of piped water coverage (NWSC 2008). This may be attributed to the requirements and costs for applying for water connections.

A transition from the unimproved water sources to piped water connections at household level has been promoted by many global initiatives. Despite the progress made, the switch between technological options is still low particularly in developing countries (UNICEF and WHO, 2012). Based on this background, it is hypothesized that recent global initiatives have focused on the innovation diffusion model and the adopter perceptions model leading to insignificant shifts in UWDS technological options. The interaction between socio-economic and demographic characteristics and the transition in UWDS technological options have long been overlooked.

This chapter aimed to test the hypothesis that economic constraint model represented by socio-economic and demographic characteristics is a suitable model to understand the transition between UWDS option. Secondly, those socio-economic characteristics have a significant relationship with the transition in proportion of users of UWDS options. A transition in UWDS has been high on the global agenda in a bid to halve the number of people without access to safe water. The study aimed to establish the relationship between socio-economic characteristics and the transition in UWDS options in Uganda.

4.3 Data and Methods

The study was based on secondary data sourced from the 1995, 2000 and 2006 Uganda Demographic Health Survey (UDHS). The 2011 UDHS Dataset was not available to the public to allow for investigations in this study. The UDHS is a survey that studies the socio-economic characteristics and conditions of households and household members for the districts of Uganda every five years. The characteristics include attributes such as age, sex, source of water, source of energy, type of sanitation facilities, building materials for household dwellings and the type of assets owned by the households. The study is carried out and funded by many development agencies such as the United Nations Children's Fund (UNICEF), the Uganda Government, the Japanese International Cooperation Agency (JICA) and the United States Development Agency (USAID).

The study was carried out on Iganga Municipal Council and Kampala City Council. Iganga was chosen because it is an emerging town that is in her early stages of the UWDS transition process. The institutions are weak, the UWDS options are at early stages of development and the socio-economic characteristics are simply in the formative stage. Hence, the barriers for UWDS transitions in Iganga are low. On the other hand, Kampala was chosen because it is the largest city in Uganda and represents a city with already developed institutions and socio-economic characteristics. In Kampala, the social dynamics and barriers to transition in Kampala are greater. Because the district specific UDHS data may not be well representative, data for the central and Eastern regions was adopted in the analysis so as to represent Kampala and Iganga, respectively. This was adopted due to time limitations and the large availability of data required for statistical models. However the limitation of this approach is the over generalisation due to a large scale of resolution.

4.3.1 Variables and their Measurements

The variables were categorized into two major groups. That is, the outcome and explanatory variables. The outcome variable was the main source of drinking water which was modelled using four outcomes such as piped water in house, yard taps or stand pipes, other improved sources and unimproved sources. This variable was considered to be nominal and the ordering of the codes assigned to each of the categories was of least importance. The potential explanatory variables were socio-economic and demographic characteristics of households in the study area. This data was selected in relation to relevant literature and in composition was limited to the following: region (Kampala vs. Iganga), rural urban residence, household size, characteristics of household heads (age, sex and highest education level) and housing characteristics (floor, roofing, and wall materials as well as electricity status.

4.3.2 Data Analysis

The data was analysed using statistical techniques in the following stages. Firstly, a distribution of the water sources in the two regions was presented using frequency distributions. The coverage was assessed across study periods 1995, 2000 and 2006. Secondly, differentials in coverage of water sources were investigated by the explanatory variables presented in prior sections using the Pearson Chi-square Test. The results were presented using cross-tabular analysis across the various study periods. Analysing the relationship between socio-economic characteristics and UWDS transitions requires advanced statistical techniques such as regression. There are two models applied in logistic regression that can be used to model this relationship. Binomial logistic regression (BNL) and multinomial logistic regression (MNL) (Wang 2005). BNL is suitable for dichotomous dependent variables whereas the MNL is suitable where the dependent variable involves more than two outcomes (Anderson 1982). Following (Bohning 1992, Wamala et al. 2011; Wang 2005) MNL was used because the outcome dependent variable is categorical - allowing for four outcomes of UWDS options (That is piped water, yard taps/stand taps, improved sources and unimproved sources). The outcome (UWDS options) of transition empirical model do not follow a particular organised order and outcomes are nominal and the residuals are not normally distributed and hence give a different output across values of the independent variables. The MNL was implemented using STATA version 11 a statistical modeling package developed by StataCorp in 1985 (StataCorp 2009) . The investigations at the three stages of analysis were investigations across the study periods (1995, 2000 and 2006). For all statistical investigations made, associations between explanatory variables and water sources, the outcome variable, were established at 5% and 1% levels because they are most widely applied (Anderson 1982; Wamala et al. 2011).

4.4 Conceptual framework and transition model for UWDS options.

4.4.1 Conceptual Model

The conceptual model for the relationship between socio-economic characteristics and the transition of UWDS follows the economic constraint theory. The economic constraint theory argues that socio-economic characteristics of potential users influence the pattern of adoption of a technology (Mazvimavi and Twomlow 2009). The model has been widely applied to model transitions and adoptions in many fields such as agriculture- to study the transition in agricultural technologies (Chi and Yamada 2002; Ferede and Bokelmann 2006) and information technology (Cassou and Xavier de Oliveira) and education (Abrahams 2010). These studies postulate that the transition/adoption in a technology is a result of user socio-economic and demographic characteristics (Idrisa et al. 2010; Patel et al. 2010). This is analogous to the problem of transitioning between UWDS options by households. Based on the economic constraint theory, the transition between a prior and posterior UWDS option depends on a household's resource endowments and its socio-economic characteristics such as rural urban residence, age and sex of household head, wealth index, household size, floor material for walls, type of toilet facility among others. Hence, the transition between UWDS options is modelled as a choice between the prior and posterior UWDS option represented by $a^{posterior}$ and a^{prior} respectively and is assumed to depend on socio-economic characteristics of a household (Idrisa et al. 2010; Patel et al. 2010). $a^{posterior}$ and a^{prior} is the state of an UWDS after and before a transition. The probability and regression coefficients of the model can be obtained using regression analysis (Ferede and Bokelmann 2006).

4.4.2 Empirical Model and Potential Socio-economic Predictors

An empirical model was developed to estimate the relationship between socio-economic attributes and the transition in UWDS options. Among the two empirical models widely used to analyse relationships and technology adoption, MNL analysis has gained importance because it can handle more than two unordered outcomes (Wang 2005) as opposed to BNL which is limited to two dichotomous outcomes (Wamala et al. 2011). MNL is used where the dependent variable is unordered and categorical in nature while the independent variables are continuous or categorical with one acting reference category (Anderson 1982). In this study, the dependent variable has more than two outcomes and the relationship between the UWDS options and socio-economic characteristics is not likely to be linear.

This study adopted MNL for the empirical model with the “unimproved sources option” denoted by “4” as the reference category. The “unimproved sources option” was adopted because it is widely used globally as a benchmark to track progress in achieving the water target of the MDGS (UNICEF and WHO 2012). Furthermore in Uganda, “ unimproved sources option” is most common type of water source option from which the existing communities have transitioned (MWE 2012).

Suppose y_i is the dependent variable with four categories for UWDS transition option i . The probability of being in category m (m=”1” [piped water], “2” [yard taps/stand taps], “3” [improved sources] and “4”[unimproved sources] can be represented by $\pi_i^{(m)} = P(Y_i = m \mid X)$ with reference to category $\pi_i^{(4)}$ (Wang 2005). Following Wang the MNL model with independent variables ($\mathbf{X}$) is denoted as:

$$In\left(\frac{\pi_i^{(m)}}{\pi_i^{(4)}}\right)=\ln\left[\frac{P(Y_i=m\,|\,\mathbf{X})}{P(Y_i=4\,|\,\mathbf{X})}\right]=\beta_m+\sum_{k=1}^{K}\beta_{mk}X_{ik} \qquad m=1,2,3,4 \quad [4\text{-}1]$$

Rewriting Equation 4-1, the likelihood of transitioning to a piped water option after five years given the prevailing independent variables rather than 'unimproved sources is given by (Wamala et al. 2011)

$$\ln\left[\frac{P(Y_i=1\,|\,\mathbf{X})}{P(Y_i=4\,|\,\mathbf{X})}\right]=\beta_1+\beta_{11}X_{11}+\beta_{12}X_{12}+\ldots+\beta_{1k}\;X_{1k} \qquad [4\text{-}2]$$

Similarly, following Wamala et al. (2011) the likelihood of transitioning to yard taps/stand taps option after five years given the prevailing independent variables rather than *'unimproved sources* based on equation 4-1, is given by the formula:

$$\ln\left[\frac{P(Y_i=2\,|\,\mathbf{X})}{P(Y_i=4\,|\,\mathbf{X})}\right]=\beta_2+\beta_{21}X_{21}+\beta_{22}X_{22}+\ldots+\beta_{2k}\;X_{2k} \qquad [4\text{-}3]$$

Lastly, the likelihood of transitioning to improved sources option after five years given the prevailing independent variables rather than 'unimproved sources' based on Equation 4-1, is given by the formula (Wamala et al. 2011) :

$$\ln\left[\frac{P(Y_i=3\,|\,\mathbf{X})}{P(Y_i=4\,|\,\mathbf{X})}\right]=\beta_3+\beta_{31}X_{31}+\beta_{32}X_{32}+\ldots+\beta_{3k}\;X_{3k} \qquad [4\text{-}4]$$

Where:

$P(Y_i=1\,|\,\mathbf{X})$ Represents the probability of transitioning to piped water after five years, given prevailing independent variables.

$P(Y_i = 2 \mid \mathbf{X})$ Represents the probability of transitioning to yard taps/stand taps after five years, given prevailing independent variables.

$P(Y_i = 3 \mid \mathbf{X})$ Represents the probability of transitioning to improved sources after five years, given prevailing independent variables.

$P(Y_i = 4 \mid \mathbf{X})$ Is probability of remaining in unimproved sources program given prevailing independent variables (which is base category).

β_{mk} Are exponential coefficients (relative risk estimates) estimated from the model while, $\mathbf{X}$ is a matrix vector of potential socio-economic characteristic predictors/independent variables that influence transitions in UWDS options.

The independent variables used in this study were eleven and these included: v101=region, v102 = type of place of residence, v149 =educational attainment, v190=wealth index, v136=number of household members, v151=sex of household head, v152=age of household head, v119 =has electricity, v116= type of toilet facility, v127= main floor material, v128=main wall material, v129 = main roof material. The details of variables (coding and measurements) are summarized in Appendix 4. The variables were used because they are readily available in UDHS. There is considerable evidence in literature that these attributes have been used as socio-economic indicators in other fields (Ferede and Bokelmann 2006; Ferguson et al. 2003; Townsend et al. 1985; Walekhwa et al. 2009).

The transition in UWDS options was investigated over a fifteen year period. In other words, the association of the transition in UWDS options with changes in socio-economic characteristics over three five year periods was investigated. During the bivariate stage of analysis, variations in the distribution of the water sources (dependent) by region (independent) are investigated using the Pearson Chi-square test. Associations were established at two levels, that is; 5% and 1% level of significance because they are commonly used (Anderson 1982; Wang 2005). Differentials in distribution of water sources by socio-demographic characteristics of respondents were presented using cross-tabular analysis and associations established using the Pearson Chi-square value and the probability value. Only socio-economic attributes with a probability value of 0.5 and below as suggested by Hilbe (2011), were considered for further investigations at the multivariate stage, unless otherwise.

4.5 Results of empirical model

4.5.1 Distribution of Water Sources

Table 4-1 represents the distribution of drinking water sources for the periods 1995, 2000 and 2006 by the two regions of Kampala (developed) and Iganga (non-developed). Variations in the distribution of the water sources (dependent) by region (independent) are investigated using the Pearson Chi-square test. Associations were established at two levels. That is 5% and 1% level of significance.

Table 4-1: Distribution of Water Sources by Region and Year of Study

Water Sources and Region	**Year of Study (%)**		
	1995**	**2000****	**2006****
Kampala			
Piped in House	529 (24.3)[a]	173 (7.6)	240 (30.8)
Yard Taps/Stand Pipes	.	558 (24.5)	364 (46.7)
Improved Sources	1596 (73.4)	992 (43.6)	122 (15.7)
Unimproved	50 (2.3)	553 (24.3)	53 (6.8)
Iganga			
Piped in House	298 (15.7)	70 (4.2)	13 (1.5)
Yard Taps/Stand Pipes	.	260 (15.6)	49 (5.8)
Improved Sources	1486 (78.1)	1054 (63.3)	625 (74.0)
Unimproved	118 (6.2)	281 (16.9)	157 (18.6)

*Note. Differentials in coverage between the two regions were investigated using Pearson Chi-square test; where *p < 0.05 and **p < 0.01*

[a] *Number of respondents by region and year of study (percentage)*

The results in Table 4-1 show a significant variation in the distribution of water sources by regions of Kampala and Iganga during the three study periods ($p < 0.01$). In the results across study period, the highest coverage of piped water sources in houses, yard taps and stand pipes was in Kampala– the developed area. For example, the proportion of houses with pipes in house by the two regions during the study period was as follows; 30.8% versus 1.5% in 2006, 7.6% versus 4.2% in 2000, and 24.3% versus 15.7% in 1995. Alternatively, improved water sources were predominant in Iganga – non-developed area. For example, the proportion of houses with improved water sources in Kampala and Iganga during the study period was as follows: 15.7% versus 74.0% in 2006, 43.6% versus 63.3% in 2000, and 73.4% versus 78.1% in 1995.

4.5.2 Socio-economic factors associated with UWDS option transition

MNL analysis was performed using STATA statistical package version 11 to determine the exponential coefficients (relative risk estimates) that indicate the importance of the socio-economic attributes and the probabilities-P (which provide an indication of significance of the coefficients) for the model in Equations 4-2 to 4-4. The focus of the analysis was to investigate differentials (if any) in the socio-economic and demographic factors by water source in the periods 1995, 2000 and 2006. The net impact of the factors was investigated with “unimproved source” as the base category. In other words, the likelihood of having piped water in house, yard taps and stand pipes as well as improved water sources, rather than unimproved sources, was investigated.

The regressions therefore enabled the identification of the socio-economic factors associated with the transition in UWDS options. This enabled to understand the implications of the observed patterns of socio-economic factors for policy changes so as to increase the uptake, efficiency and costs for UWDS transitions.

Table 4-2 presents the socio-economic factors associated with the transition in UWDS options. It shows the exponential coefficients β_{mk} for an UWDS transition option m derived from the empirical models in Equation 4-2 to 4-4 above. A (-) value represents negative correlation while a (+) value represents positive correlation. The values in column 1 from the left represent the exponential coefficients $\beta_{pipedwater}$ of the socio-economic indicators for the empirical model in Equation 4-2. On the other hand, column 2 represents the exponential coefficients $\beta_{yardtaps}$ of the socio-economic indicators for the empirical model in Equation 4-3. Lastly, column 3 represents the exponential coefficients $\beta_{improvedso\ urces}$ of the socio-economic indicators for the empirical model in Equation 4-4. These equations have been derived for each of the transition periods 1995, 2000 and 2006.

The model provided in Table 4-2 is significant at 1% and 5% indicated by (**) and (*) respectively. Based on Wamala et al (2011), coefficients greater that 5% are often ignored. Hence, coefficients not within the 95% confidence interval are not indicated with a (**) or (*). For example, in 1995 with coefficients of correlation of -3.44 and -0.67 respectively, the socio-economic characteristic of being a rural resident or the region of Iganga had a negative and significant influence on the UWDS option of piped water ($p < 0.01$). This interpretation is used to understand the association of the different factors with UWDS transitions as elaborated below

Table 4-2: Multinomial Logistic Regression estimates of the UWDS options transition model during 1995, 2000 and 2006

Independent Variables	*1995*			*2000*			*2006*		
	Pipes[a]	**Yard Taps**[b]	**Improved**	**Pipes**	**Yard Taps**	**Improved**	**Pipes**	**Yard Taps**	**Improved**
Residence									
Urban[†]	.	.	.	.	.	.	.	.	.
Rural	-3.44**	.	-0.47	-3.02**	-4.4**	0.30*	-17.74	-3.38**	1.60**
Region									
Kampala[†]	.	.	.	.	.	.	.	.	.
Iganga	-0.67**	.	-0.78**	0.60*	0.79**	0.76**	-0.39	0.33	-0.34
Education Level									
None[†]	.	.	.	.	.	.	.	.	.
Primary	0.17	.	0.53**	0.16	-1.17	0.04	0.10	-0.53	0.06
Secondary	0.04	.	0.36	0.26	-0.52*	-0.31	0.14	-0.29	0.04
Higher	10.94		11.88	1.11	-0.38	0.10	0.67	-0.26	-0.06
Age of Head									
29 Below[†]	.	.	.	.	.	.	.	.	.
30-39	0.02	.	-0.08	0.50	0.05	0.08	0.59	0.59*	0.28
40-49	0.10	.	0.26	-0.33	0.08	0.10	0.11	-0.16	0.36
50 Above	-0.48	.	-0.14	-0.17	0.51	-0.01	0.11	-0.53	-0.19
Sex of Head									
Male[†]	.	.	.	.	.	.	.	.	.
Female	0.05	.	-0.23	0.32	0.16	0.16	-0.35	-0.01	0.39*
Household Size									
1-4[†]	.	.	.	.	.	.	.	.	.
5-9	-0.34	.	-0.28	0.24	-0.46**	-0.03	0.23	0.07	-0.07
10 Above	0.01	.	0.30	0.01	-0.94**	-0.29*	0.90	0.78*	-0.21
Housing Characteristics									
Electricity									
No[†]	.	.	.	.	.	.	.	.	.
Yes	0.44	.	0.17	1.36**	0.58**	-0.02	1.23**	0.35	-0.21

Table 4-2: Cont’

Type of Toilet									
Flush[†]	.	.	.	.	.	.	.	.	.
Pit Latrine	-14.06		-11.42	-2.81**	-0.34	0.81	-2.32**	0.26	1.13
VIP	-15.18		-12.04	-3.68**	-1.02	0.02	-1.86*	0.31	1.16
Other	-15.27		-11.42	-3.17**	-1.55*	-0.03	-2.95	-15.01	0.39
Main Floor Material									
Natural/Earth[†]	.	.	.	.	.	.	.	.	.
Finished/Tiled	.	.	.	1.88**	0.29	0.23	1.22	-0.66	-1.52*
Cement	.			.	.	.	0.62	0.71*	0.47
Main Wall Material									
Natural/Rudimentary[†]	.	.	.	.	.	.	.	.	.
Finished/Cement	.	.	.	0.63	-0.34	-0.25	0.52	-0.05	-0.33
Other				.	.	.	2.59	1.51	-0.14
Main Roof Material									
Natural/Rudimentary[†]	.	.	.	.	.	.	.	.	.
Iron Sheets	.	.	.	14.4	14.02	12.6	-0.21	16.30	0.62**
Tiles/Asbestos	.	.	.	-10.6	-12.2	-2.49**	-0.10	16.48	0.87

Note. Base category is “Unimproved sources”; $^{**}p < 0.01$ *and* $^{*}p < 0.05$

(**) and (*) indicates the level of significance of the exponential coefficients of the model

[a] Likelihood of piped water in house rather than unimproved sources

[b] Likelihood of yard taps and stand pipes rather than unimproved sources

[c] Likelihood of improved sources rather than unimproved sources

[†] Reference categories adopted in the investigation

Residence

Unlike the period 2006 piped water sources, rather than the unimproved, were less likely to be in the rural areas compared to the urban during the period 1995 and 2000 ($p < 0.01$). Further, the periods 2000 and 2006 were less likely to have yard taps ($p < 0.05$). Likewise, improved sources were more likely to be in rural areas across the periods 2000 and 2006 ($p < 0.05$). These results are expected and are consistent with the findings of the JMP report which found that the most common type of water sources in the 1990s was over 51% (UNICEF and WHO 2012).

Region

Unlike the 1995 period where the under-developed region of Iganga was less likely to have piped water source in house, rather than unimproved sources, compared to Kampala ($p < 0.01$). No significant difference in piped water source was noted in the subsequent periods of 2000 and 2006 ($p > 0.05$). By 2006, no significant variation in water sources was observed between Kampala (developed) and Iganga (under developed). The results suggest a similar distribution of water sources across the developed and under developed region in the period 2000. This can be attributed to the fact that Kampala having achieved greater piped water coverage and has reached its maximum. On the other hand, Iganga has been growing rapidly and hence experienced rapid transition in the UWDS options.

Education Level

With the exception of a few significant variations noted, the highest education level of the household head did not play a major role with regards to water source distribution ($p > 0.05$). During 1995, improved sources rather than unimproved were more likely among respondents with primary education. On the other hand, yard taps were less likely among respondents with secondary education level during the period 2000.

Sex of Head

No significant variations in coverage of yard taps and piped water in house were noted across the periods 1995, 2000 and 2006 ($p > 0.05$). However, unlike the period 1995 and 2000; improved sources rather than the unimproved were more likely among the female headed ($p < 0.05$).

Household Size

Across the study period, likelihood of piped water sources rather than the unimproved did not vary significantly by household size ($p > 0.05$). Unlike the period 2000, were yard taps were less likely among households with a large family sizes of over 10 members compared to that with at most 4 members, yard taps in 2006 were more likely among households with larger family sizes of over members ($p < 0.05$) .

Electricity Status

Unlike the period 1995, piped water sources were more likely among households with electricity compared to those without ($p < 0.05$). Unique to the period 2000, yard taps were more likely among households with electricity compared to those without ($p < 0.05$).

Type of Toilet

Unlike the period 1995, houses with pit latrines, VIP and other types of toilets in 2000 and 2006 were less likely to have piped water in house compared to those with flush toilets ($p < 0.05$).

Main Floor Material

In 1995, data on this variable was not compiled; however, houses with furnished or tiled floor materials were more likely to have piped water in house compared to their counterparts with natural or earth materials ($p < 0.05$). In 2006, households with furnished or tiled floor materials were more likely to have improved sources compared to those with natural or earth materials. On the other hand, those with cement floors in the 2006 were more likely to have yard taps, rather than unimproved, compared to those with natural or earth materials.

Main Wall Material

No significant variation in coverage of water sources across house wall materials was noted across the periods 1995, 2000 and 2006 ($p > 0.05$).

Main Roof Material

There was no significant variation in the coverage of piped water in house and yard taps during the periods 2000 and 2006 ($p > 0.05$). However, improved sources in 2000 were more likely among households with tiles/asbestos compared to those with rudimentary facilities. In 2006, improved sources, rather than unimproved, were more likely among households with iron sheets or cement compared to those with the rudimentary ($p < 0.05$).

Unlike the rural urban residence which was consistent across the periods 1995, 2000 and 2006; significance (if any) by the rest of the variables adopted in the study varied across the periods (see, Table 4-2). This suggests that the contribution of these variables with regard to the distribution of water sources is not constant over time. In other words, one cannot adopt a constant model in establishing the coverage of water sources. None the less, based on the results, socio-economic characteristics are associated with UWDS options.

4.6 Discussions of Results

This research is the first to look at the relationship between socio-economic characteristics and UWDS transitions and researchers investigated the association of socio-economic characteristics in other areas such as the health sector (Ferguson et al. 2003; Townsend et al. 1985), technology adoption (Ferede and Bokelmann 2006; Popp et al. 2011; Walekhwa et al. 2009). However, these serve other fields and have not been tested on UWDS. Unlike previous regression models in technology adoption that are based on dichotomous outcomes, this study focused on unordered polychotomous outcomes of UWDS transition options. Determination of the exponential coefficients and probabilities in this study has been performed using STATA statistical package version 11.

The socio-economic characteristics found to be significantly associated with the transition in UWDS options are electricity connection and type of toilet facility. This could potentially impact the ability to influence the transition between UWDS options for the communities in Iganga Municipality and Kampala City that are either not connected to electricity, do not have a toilet facility or both. Furthermore, research should be expanded to identify the perceptions of the communities that utilise the UWDS options that influence the transition between UWDS options in Kampala and Iganga. These could be modelled together with socio-economic characteristics to accelerate the rate of uptake and transition between UWDS options in Kampala and Iganga.

The fact that electricity is significant agrees with the findings of Townsend et al (1985) based on 28 wards of the city of Bristol, England that there is a significant relationship between households connected to the electricity grid and their socio-economic statuses. This also agrees with the findings of Ferguson et al (2003) at a statistical significance of 0.039, that there is a relationship between electricity connections based on empirical data for the 1991 Pakistan Integrated Household Survey. These factors are further confirmed by the Multidimensional Poverty Index (MPI). The MPI is a multidimensional index used to classify socio-economic status in developing countries. Developed by the Oxford Poverty & Human Development Initiative in conjunction with United Nations Development Programme, the index highlights both electricity ownership and type of toilet facility as one of the indicators used to describe the living standards dimension in the MPI (Alkire and Foster 2011). These two attributes are essential for the UWDS transition process. In Uganda, it is generally believed that electricity is a yard stick that distinguishes between a socio-economic status between a developed location and a developing area.

The study results show that planners and engineers in the urban water sector ought to adopt a holistic approach that enable designing, developing and recommending new technologies without correlating the most significant socio-economic attributes of the community associated with the transition of UWDS options. Socio-economic attributes associated with the transition in UWDS options are desirable. Based on these attributes, UWDS designers can develop innovative UWDS approaches, policies and options that blend with socio-economic characteristics of communities. This confirms that transitions in UWDS options are socio-technical.

CHAPTER FIVE

DESIGN FOR URBAN WATER DISTRIBUTION SYSTEM TRANSITIONABILITY

5. Introduction

Contemporary design for upgrading UWDS is based on 19^{th} century principles biased towards the objective of improving the levels of service of the UWDS. Populations were relatively small and sustainability was not among the critical design criteria at the time. Nowadays, drawing from the sustainability definition developed by the Brundtland Commission in a 1987 United Nations Report and due to emerging sustainability guidance (OFWAT 2009) the aforementioned design principles are no longer appropriate.

Moreover, transitioning UWDS in the future will be more challenging due to the ever changing global pressures such as population growth, urbanisation, climate change and anthropogenic changes which are set to increase water demand; thereby impacting on the performance of existing UWDS during their lifespan. Presently, accurate prediction of these change pressures is still elusive. To deal with these uncertainties, the design of transitionable UWDS is proposed. Hence, the need for explicit consideration of transition costs during the design/upgrade of UWDS is warranted.

Transitioning costs are the costs related to ensuring that UWDS overcome the inertia embedded in the technical, socio-economic, institutional and financial subsystems inherent in the incumbent system. However, the challenge is to identify a pipe or pipe cohorts that can be retained in an UWDS without impacting the costs and performance of the UWDS. Relatively large transition costs lead to lock-in. Technological lock-in and its implication on the transitionability of technological systems has been studied in many fields: carbon (Unruh 2002), technological systems (Windrum 1999) energy (Könnölä et al. 2008); environmental management (Könnölä 2005). However, its investigation in the UWDS is in its infancy. The determinants of technological lock-in are still a subject of academic inquiry and can be broadly classified as technical, socio-economic, institutional and financial factors (Unruh 2000). To design UWDS that do not lock us in, the upgrade of existing UWDS aspire to minimize costs for transitioning existing UWDS both now and in the future. This necessitates among others, lowering switching costs when upgrading UWDS while adapting to the change pressures.

Recent research on minimizing transition costs for UWDS has been studied from the perspective of design for flexible UWDS. Flexible design for UWDS presented by Zhou and Hu (2009) Sieker et al (2010) Huang et al (2010) is an approach for the identification and embedding flexible sources in urban water systems. The shortcoming with these approaches is that it is suitable for new UWDS rather than for existing systems. Moreover, the approach has not been applied to existing UWDS. On the other hand, the concept of design for changeability (Fricke and Schulz 2005; Hashemian 2005) emphasizes the need to design systems that can be transitioned and evolved at a minimum cost. The approaches aim to minimize switching/transition costs during the life cycle of the system which is taken at time intervals and phases. The draw back with these approaches is that they have not been populated with real quantitative data and have not been tested and applied to UWDS.

Chapter 3 presented an approach for the quantification of socio-economic impacts due to UWDS transitions. Chapter 4 presented an approach for the association of UWDS transitions and socio-economic characteristics. This chapter develops a paradigm shift for urban infrastructure managers and planners while upgrading UWDS. It departs from the conventional optimisation based approaches that rarely consider future transitionability of UWDS. The conventional optimisation only include leakage and burst costs during UWDS upgrade in considering minimisation of technical impacts, operation and maintenance impacts, and social impacts during UWDS transitions. This is due to the need to minimize both technical and socio-economic transition costs for sustainable UWDS upgrades by water utilities. Drawing from the definition of sustainability (Brundtland Commission, 1987), upgrade of UWDS should not only meet the present requirements but should also have the capability to be transitioned at a minimal socio-economic and technical impacts cost.

The main questions for the chapter are; how can UWDS transition costs be quantified?; How can the costs and impacts for transitioning UWDS be minimized during the lifecycle of the UWDS? . To address the above questions, this Chapter is structured in ten sections. Section 5.1 introduces and gives a brief overview of the design for UWDS transitionability. Section 5.2 presents the theoretical and conceptual framework for the UWDS transition problem. In the section, theoretical concepts such as the graph transition systems, the product platform concept and morphing algorithms used to define the problem are presented. The metrics for the quantification and measurement of transitionability are also presented in this section. The characterisation of the UWDS transitionability design problem is described in Section 5.3. Section 5.4 presents the approach called the UWDS transition impact assessment methodology (UTIAM) to identify pipes and pipe cohorts that have the least impact on the future transition of UWDS. The approach is based on a combination of pipe and pipe cohort transition impact analysis and the product platform concept. The costs and impacts are appraised by evaluating the technical transition impact costs, the socio transition impact costs and the system operation and maintenance transition impact costs associated with transitioning a pipe and pipe cohort. Section 5.5 presents a brief on genetic algorithms used in determining the pipe transition impact cost. Section 5.6 presents the application of the developed design methodology on a hypothetical case study as a proof of concept. Section 5.7 presents the benefits for the conventional transition and the UWDS transition approach are compared. Finally, Section 5.8 presents the results discussion

5.1 Conceptual Framework for the Design for UWDS Transitionability

To conceptualize the design for UWDS transitionability, we draw on a combination of theory from. The image morphing, product platforms and graph transitions. Morphing is a technique that is used to model the transition between two successive images (Gao and Sederberg 1998; Wolberg 1998). The concept is now widely used to process the seamless transition between video images such as Michael Jackson's Black or White (Aboul-Ella and Nakajima 1998). This is analogous to the UWDS transition problem that aims to transition UWDS between the present and future states. The morphing problem minimises the impact as images transition between two states. Mathematically, this is represented by image warping + cross dissolving (Tal and Elber 1999). The correspondence between two images represents the change between two states of the UWDS. On the other hand, the minimisation of the energy required to transition from one image to other corresponds to the minimisation of the transition cost and effort required to transition between UWDS.

In the UWDS transition problem, the two images, source and destination images in morphing can be represented by the source and destination graph in the UWDS transition problem (Alonso, Alvarruiz et al. 2000; Deuerlein 2008; Sempewo et al. 2008). Graph theory enables the structuring of the UWDS transition problem and to pre-process the UWDS for the warping process. On the other hand, graph transition systems can be used to make a meaningful representation of states and transitions of an UWDS. The concept of graph transition systems is widely applied in computer science to model and represent graphs and graph morphisms (Alur et al. 1992; Edelkamp et al. 2005; Bradeld and Stirling 2009).

One of the key precepts in image morphing is the minimisation of the changes to some components of the image. Hence, features of image that remain uniform throughout the transition process are preserved. This helps to minimise the energy required to seamless transition the image. Hence, with respect to the UWDS transition problem it is hypothesised that maintaining components of the UWDS reduces UWDS transition costs and efforts. This brings the concept of product platform. Based on this concept, optimal pipes and pipe cohorts with the least impact on future transitions can be identified. The Product platforms concept is a suitable framework for designing engineering components with the least impact on future uncertainties and changes(Meyer 1997; Muffatto 1999; Gonzalez-Zugasti, Otto et al. 2000; Simpson, Maier et al. 2001). Detailed of the concept can be found in Dai and Scott (2007).

A transition between UWDS can be represented as $T_{UWDS} = (U^o, U^T)$ where U^o is the prior state of the UWDS U^T is the posterior state of the UWDS and T_{UWDS} = UWDS transition.

Let U represent the hydraulic and geometric characteristics of an UWDS at different time periods. Thus, $U^i=U^{i-1} + tc^i$, i=1,2,….,T defined the path of an UWDS during the transition process $U^o \xrightarrow{tc^1} U^1 \xrightarrow{tc^2} U^2,.....,U^{T-2} \xrightarrow{tc^{T-1}} U^{T-1} \xrightarrow{tc^T} U^T$, where tc^i is the transition cost and impact of U between configurations $UWDS^i$ and $UWDS^{i-1}$. U^o and U^T are defined by the source and target UWDS respectively.

The UWDS transition cost t_c can be obtained from pipe transition impact cost (PTIC). PTIC can be computed from the surrogate of the cost of redesigning the pipes and pipe cohorts subject to maintaining a pipe and group of incumbent pipes in a future UWDS.

The states of the UWDS can either be functional or spatial/geometric (Bradeld and Stirling 2009) The functional state could be represented by the hydraulic characteristics and the level of performance of the UWDS in delivering the required quantity and quality of water. On the other hand, the geometric states represent the structure and geometric characteristic of the UWDS in space and time. The determinants of the geometric characteristics are the location of demands and the terrain. So graph theory provides a natural way to represent geometric and functional states for an UWDS transition.

A graph G consists of two distinct subsets of elements (N, P) with element N (D) representing either vertices and P (D) representing edges of the graph. Putting this in the analogy of an UWDS, the network can be decomposed into nodes and links representing water consumption points and links respectively (Sempewo et al. 2008). The approach of decomposition of an UWDS into a graph is well documented (Eiger et al. 1994; Deuerlein 2008; Sempewo et al.

2008). Hence, the UWDS transition states U^O and U^T are represented by two graphs. That is source and destination graphs G^O and G^T respectively. G^O is a weighted graph for an existing system represented as $\langle V_P, E_P, Ext_{WS\,G}, Fut_{WSG}, \omega_G \rangle$ where V_P represents nodes, E_P represents edges, Ext_{WSG}, Fut_{WSG} : $E_P \rightarrow V_P$ are functions that describe the origin and destination graph and $\omega : E_P \rightarrow A$ is a weight. On the other hand, for the optimised future system G^T is a represented by $\langle V_F, E_F, Fut_{WSG}, \omega_F \rangle$. The original graph (existing UWDS) from which transitions are to originate is denoted $s_o G$.

Since the characteristics and states of the UWDS change in time, the characteristics of the UWDS represented by a graph change as well. The concept of graph transition systems is adopted to represent the states of the UWDS in transition.

5.1.1 The Proposed Approach-UTIAM Methodology

A suitable approach proposed in this chapter for evaluating the plausibility of UWDS transition options in the future is the UWDS transition impact assessment method hereinafter known as UTIAM. The UTIAM methodology is based on quantification of transition impacts due to pipes and pipe cohorts in a future UWDS based on a range of UWDS demand scenarios for the future. The rationale of the UTIAM approach is based on the assumption that UWDS pipes and pipe cohorts can be ranked based on their impact on the future transitionability of the system (PTIC). This metric of PTIC can be used to eliminate pipes with a relatively higher impact on the transitionability of the future UWDS. The foundation for the design approach is in determining which pipes and pipe cohorts are likely to cause relatively large UWDS transition cost/impact and how these can be strategically minimized to minimize transition costs while maximizing performance. The UTIAM methodology consists of five steps. They include: design plausible options for embedding transitionability in UWDS, develop scenarios for future UWDS, quantify UWDS transition impacts, evaluation-comparison and selection of the UWDS transition option, and detailed design for UWDS Transitionability based on the selected UTDO.

Plausible options for transitioning UWDS are developed and these include the UWDS transition platform option that consists of fixed platform and variable elements. The platform elements remain static while the variable elements are transitioned during the transition of the UWDS. The second option is the conventional approach based on legacy design principles that do not consider future change costs. After developing the UTDO, scenarios for the future UWDS are created against which the life cycle costs/impacts for each of the transition options are evaluated.

Development of the UWDS transition model is based on the assumption that the favoured future state is known. Various approaches exist in literature for estimating demand scenarios, such as probabilistic scenarios and deterministic scenarios. However, for this study a deterministic demand estimation approach has been used because it best represents the transitioning nature of the UWDS. So demand scenarios are created based on anticipated future trends of UWDS based on the “Increased demand” scenario where rapid population growth and urbanization is assumed to cause an increase in demand beyond the normal growth rates of say 10% .

The next stage is to compute the cost for transitioning the UWDS between transition states/scenarios. This is because elaborated upgrade costs are technically biased. For the UTIAM, we assume that UWDS transition costs consist of:

(i) Technical impact costs (TIC) related to redesigning the UWDS to cause a transition from the incumbent UWDS to a desired UWDS.

(ii) Socio-economic impact costs due to UWDS technical transitions.

Technical transition impact cost (TIC) is derived from the cost for redesigning the incumbent UWDS to develop a desired UWDS with an acceptable service level in tandem with the global change pressures. Hence, the cost for transitioning from $UWDS_1$ to $UWDS_2$ is the additional cost required to create $UWDS_2$ from $UWDS_1$. Depending on the UTDO, this may involve maintaining pipes and pipe cohorts from $UWDS_1$ in $UWDS_2$ as well as redesigning the components likely to increase UWDS transition costs. The UWDO considered are those that assume a common platform while the other option considers elements that UWDS with no designed commonality and platforms between the $UWDS_1$ and $UWDS_{2.}$ Once UWDS transition costs have been computed, the options are evaluated and the most suitable option is selected based on the UWDS transition life cycle costs.

5.1.2 Metrics for UWDS Transitionability

For the case of transitioning an UWDS, the existing system is re-optimised to meet new demand and growth which may have not been anticipated during the design of the UWDS. For an UWDS transition, this involves many criteria that can be analysed using the utility value analysis methodology that is widely applied in other fields (Richardson 1994; Siddiqi 2006). The approach enables the combination of the different performance attributes of the UWDS into a composite metric based on weights and utility functions. A key assumption is that performance is the surrogate for utility (Siddiqi 2006). This approach has also been successfully used to quantify reconfigurable space systems (Siddiqi 2006).

Transition impact assessment method (Network Transition Score)

A new transition impact assessment methodology called the Network transition score (NTS) is introduced that evaluates the performance of a transition in various cycles. The methodology is proposed because transitioning an UWDS may impact the performance of the system. The proposed UTIAM ensures that the impacts on the performance on the UWDS are minimised. The approach is based on evaluation of the performance of a candidate transition option for different future UWDS transition states. It is in effect a measure of performance deviation due to a particular transition-either due to an element or group of elements (NTS).

The ratio $NTS = \frac{P_{ctn}}{P_{fn}}$ is the network transition score.

Where: P_{ctn} - performance of the optimised future UWDS and P_{fn} - performance for the candidate UWDS. The hydraulic performance is calculated based on resilience index (Todini 2000) a method that is widely used to assess the performance of UWDS. Substituting the formulation for performance in the NTS formulation gives

$$NTS = \frac{MRI_{ctn}}{MRI_{fn}} = \frac{\sum_{j=1}^{Pctn} Q_j^{ctn}(H_j - H_{\min,j})}{\sum_{j=1}^{Pctn} Q_j^{ctn} H_{\min,j}} x \frac{\sum_{j=1}^{Pfn} Q_j^{fn} H_{\min,j}}{\sum_{j=1}^{Pfn} Q_j^{fn}(H_j - H_{\min,j})} \quad [5\text{-}1]$$

Where MRI = percentage of ratio of nodal surplus power available to the sum of the minimum required power at the demand nodes. For the UWDS transition problem this can be the ratio of the summation of the surplus power of the candidate UWDS transition to the optimised future UWDS.

UWDS transition cost

The metric for the cost of transitioning the UWDS shows difficulty and effort required to transition an UWDS from its current state to a desired state. The metric is a surrogate of the effort required to transition and UWDS. The metric is represented by transition impact cost (PTIC). Because transitions take place in phases throughout the life of the UWDS, transition impacts across a life cycle rather than for a single transition phase are considered. The costs included in the formulation of PTIC include social impact costs, technical impacts, operation and maintenance impacts, and social impacts during UWDS transitions. The operation and maintenance costs include burst repair impact costs and leakage repair impact costs. Details of PTIC can be found in elaborated in Section 5.2.1.

To combine the performance metric and UWDS transition cost, the utility value approach which is in effect the ratio of cost and performance is used. The measure captures the impact of the candidate transition on both performance and cost. So, transitionability is a function of (cost, performance). For simplicity, it is assumed that cost and performance have equal weight. The metric for transitionability is defined from:

$$\left(\frac{C_{ctn}}{C_{fn}} * \frac{P_{fn}}{P_{ctn}}\right) \qquad [5\text{-}2]$$

$$= \delta_C \delta_P$$

Where:

δ_C is the standardised cost of a candidate transitioned UWDS

δ_P= (NTS) is the ratio of the performance of the candidate UWDS to be transitioned to the optimised future UWDS.

C_{fn} is the cost of the optimised future UWDS

C_{ctn} is based on PTIC for the candidate UWDS

Because the cost and performance are expressed in different units, combining these units has to be done using a standardised scale. This is termed as standardisation (Figueira et al. 2005) which has been widely applied in many fields to bring measures of different units into one uniform unit that ranges between 0 and 1. Standardization is used to transform the values of the constituents of the UWDS transitionability into one uniform unit that can be combined. The standardisation formula applied is shown below

$$\text{Standardised score} = \frac{\text{Raw score}}{\text{Maximum raw score}} \qquad [5\text{-}3]$$

Where the raw scores are the pipe transition impact cost (PTIC) and the NTS obtained for each UWDS transition option.

5.2 Characterization of the UWDS Transitionability Design Problem

In general, the proposed model does not only focus on the conventional approach of optimising pipe sizes based on technical and economic aspects but also considers the minimising future UWDS transition costs and impacts to the transition of the system. This ensures that changes made to existing UWDS do not solve current system constraints while causing relatively high transition costs in the future. Because of the changes in the design requirements, the conventional design objectives which are to minimise capital cost-in terms of construction costs and operation and maintenance costs, to maximise performance in terms of pressures, flows and velocity, and maximise benefit in terms of reliability are reformulated to take care of the transition design objective.

The minimisation of capital costs as well as operation and maintenance cost is one of the main design objectives when designing UWDS. It deals with the design parameters related to replacement, repair and or extension of the pipe so as to achieve the minimum set performance levels of the UWDS. For the UWDS transition design problem, this includes the cost for resizing pipe diameters consistent with the new changed requirements and is referred to as the technical impact cost in this chapter. To build the transition impact cost function, the operation and maintenance costs due to a particular transition option ought to be included in the cost function. UWDS maintenance costs can be broadly classified as: repair costs, pipe replacement costs and cleaning costs. To transition an UWDS, two types of costs are anticipated. These are the cost of transitioning the UWDS and the cost operation and maintaining the UWDS as the other components are being transitioned. To compute these two costs, the UWDS transition platform is proposed. The method for developing the platform is discussed in Section 5.3 .

The platform is composed of the fixed pipes and variable pipes. The costs for the transitioning the UWDS is assessed from the variable part of the platform. In this study, this component of the cost will be obtained from PTIC elaborated in Section 5.2.1. On the other hand, the costs for operation and maintenance are derived from the fixed part of the UWDS transition platform. In this study, the operation and maintenance impact cost costs considered are the pipe and pipe cohort impact costs due to pipe failure and pipe bursts (BIC) and the impact costs due to water leakage (LIC). These costs are considered because they are the most widely used with well documented formulations in technical literature (Dandy and Engelhardt 2001; Mutikanga et al. 2008). The second objective of maximisation of the performance of the UWDS acts as the constraint of the optimisation process to ensure the transition options obtained meet the minimum levels of service for UWDS.

In addition to the transition impact costs, the socio-economic impact costs ought to be taken care of. These are treated as another objective in order to compare the impact of the different transition options and are represented by SII developed in Chapter 3. The indicator takes care of socio-economic characteristics of the communities where the transitions are to be implemented such as the urban characteristics, the urban infrastructure and the social and demographic characteristics.

Although relationships between socio-economic costs and technical cost can take many forms, the linear form is adopted in this study because it is the most widely used and tested on case studies in Adelaide a city in Australia (Dandy and Engelhardt 2001) and in Luwero in Uganda (Tanyimboh and Kalungi 2008).

5.2.1 Transition Impact Cost (PTIC)

The cost due to UWDS transitions need to take care of the PTIC impact of the pipes and pipe cohorts on future transitions of the UWDS. PTIC was derived from the transition operation and maintenance impact costs (OIC) and technical impact cost (TIC). The first component TIC is computed as a surrogate of the technical impact cost due to UWDS transition. It is computed from the cost for re-optimising the UWDS when a pipe or pipe cohort is retained in the UWDS.

5.2.1.1 Technical Impact Cost

The rationale for the TIC is based on the assumption that UWDS pipes and pipe cohorts can be ranked based on their impact on the future transitionability of the system. The hypothesis is that ranking of pipes based on their impact on the future transitionability of the system can be used to identify constituent pipes and pipe cohorts of an UWDS transition platform with potentially the least impact on the future transitionability of the UWDS. The approach can be used to eliminate pipes with a relatively higher impact on the transitionability of the future UWDS.

The PTIC is derived from a matrix [T] of pipe replacement costs (re-optimising a pipe diameter of each pipe) with respect to a pipe or pipe cohort being retained in a desired future UWDS.

$$[T]=\begin{bmatrix} \frac{\partial CPipe_1}{Pipe_1}\cdots\frac{\partial CPipe_1}{Pipe_j}\cdots\frac{\partial CPipe_1}{Pipe_{np}} \\ \\ \frac{\partial CPipe_i}{Pipe_1}\cdots\frac{\partial CPipe_i}{Pipe_j}\cdots\frac{\partial CPipe_i}{Pipe_j} \\ \\ \frac{\partial CPipe_n}{Pipe_1}\cdots\frac{\partial CPipe_n}{Pipe_n}\cdots\frac{\partial CPipe}{Pipe_{np}} \end{bmatrix} \qquad [5\text{-}4]$$

Where CPipe= Cost of pipe replacement with respect to a pipe or pipe cohort ($Pipe_j$) being retained in a desired future UWDS

The matrix T is obtained from heuristic search re-optimising a network pipe diameters based on a genetic algorithm (GA) optimisation linked with EPANET2 (Rossman 2000). The algorithm determines the optimal diameter from a set of discrete diameters that ensures hydraulic balance and minimum pressure requirements when a pipe or pipe cohort (Pipej) is retained in a desired future. After determining values of vector T, a vector of PTIC can be obtained from the summation of the rows of the vector [T]. This creates a cost matrix of a PTIC with respect to fixing pipes and pipe cohorts as shown in Equation 5.5.

$$\begin{bmatrix} PTIC_1 \\ . \\ . \\ PTIC_j \\ . \\ . \\ PTIC_n \end{bmatrix} = \begin{bmatrix} \sum_{pipe=1}^{np} \frac{\partial CPipe_1}{Pipe} \\ \\ \sum_{pipe=1}^{np} \frac{\partial CPipe_j}{Pipe} \\ \\ . \\ \sum_{pipe=1}^{np} \frac{\partial CPipe_n}{Pipe} \end{bmatrix} \qquad [5\text{-}5]$$

Where PTICj = pipe transition impact cost due to pipe j. It is the measure of the cost and effort required to re-optimise an UWDS when a pipe or pipe cohort is retained in an UWDS. As stated earlier the UWDS transition impacts should consider technical impacts, operation and maintenance impacts, and social impacts during UWDS transitions. The formulation of PTIC is composed of

$$PTIC_i = \frac{(1+\alpha_j)}{(1+r)^{tp}} * (W_{TIC} * TIC_i + W_{OIC} * OIC_i) \qquad [5\text{-}6]$$

Where WTIC=weight of technical impact cost (TIC), W_{OIC}= weight of operation and maintenance impact cost (OIC and tp is the duration of the transition cycle. α_i is the social transition impact cost factor (SIC) derived from

$$SIC_i = \alpha_i = PSI \;\; * SII \qquad [5\text{-}7]$$

Where SII is the socio-economic transition impact index of a pipe obtained in Chapter 3 and PSI is the pipe significant index for a pipe presented by (Arulraj and Rao 1995) given by

$$PSI_i = \frac{Q_i L_i}{C_i Dia_i} \qquad [5\text{-}8]$$

Where Dia_i is diameter (m), L_i is the pipe length (m), Q_i is the Flow (m^3/s) and C_i is the roughness coefficient of pipe i.

5.2.1.2 Operation and Maintenance Impact Cost (OIC)

Two costs are associated with OIC. The first one water leakage cost (LIC) includes the costs of leakage due to elements of the UWDS transition platform retained in the incumbent system. The second term burst cost (BIC) involves the cost of repairing bursts due to retained elements of the UWDS

$$OIC=LIC+BIC \qquad [5\text{-}9]$$

The method used to estimate the LIC is based on the approach developed by Vela et al (1991) as shown in Equation 5-10 that adds an age and diameter of a pipe term to the pressure leakage relationship developed by Germanopolous (1985). The approach has been used to analyse leakage in Kampala (Mujuni 2010) and is adopted to analyse leakage in this chapter

$$LIC = LC * tp * KL_i \times Dia_i^d \times e^{a\tau}\left(P_{ij}^{bv}\right)^{LE} \qquad [5\text{-}10]$$

Where K is a pipe constant that depends on pipe material-0.0045 for HDPE and UPVC and 0.001 for GI and Steel (Vela et al. 1991), L_i is pipe length for pipe i, Dia_i is pipe diameter of pipe i, b = Leakage shape parameter, τ = age of the pipe, LC=Leakage unit cost which is estimated from the unit cost a customer pays per m3 of water used. This is 2.2 pound sterling (£)/m^3/year (Awad et al. 2008). LE is the leakage exponent. In this study this is assumed to be 1.18 (Mujuni

2010). The term burst cost factor (BCF) in the formulation for burst impact cost is replaced by the SIC in Equation 5-12

$$PBR_{ij} = 0.002\exp(-0.01 Dia_{ij})\tau^2 \qquad [5\text{-}11]$$

$$BIC = \frac{PBR_i * L_i * SIC * CB * tp}{(1+r)^{tp}} \qquad [5\text{-}12]$$

Where PBR-pipe break rate for pipe i [pipe burst/km/year], CB=Burst repair mean cost, SIC=Socio-economic Impact Cost, r=discount rate and tp is the duration of the transition cycle. Because the units for OIC and TIC are expressed in unit costs, combining these units did not require standardisation to a similar scale.

5.3 Objective Function for Design of an UWDS Transition Platform

The conventional formulation for the UWDS upgrade problem in Equation 5-14 is reformulated to become

$$\text{Minimise } f_{cost}(U_i) = \text{minimize } \sum_{i=1}^{NOP} C_i L_i D_i \qquad [5\text{-}13]$$

$$\text{Subject to} \qquad Minimize = \sum_{j=1}^{NN} \gamma \,|\, H_j - H_{actual\,j} \,|_i \qquad [5\text{-}14]$$

In this problem the decision variables are the pipe diameters, where $C_iL_iD_i$ is the cost of pipe i of a diameter Dia_i, NOP=number of pipes in UWDS, j=node index, i=pipe index, NN=number of nodes in the UWDS. H_j= minimum allowable pressure, H_{actual}=actual nodal pressure and γ= penalty factor.

The application of the above optimisation problem on multiple transition phases ($UWDS_1$......$UWDS_T$) means there can be some commonality between the pipes and pipe cohorts of the UWDS during the transition process. It is envisaged that exploitation of this commonality will minimize UWDS transition costs. This is termed as a product platform and has been widely used to reduce production costs in an ever changing environment (Gonzalez-Zugasti et al. 2000). Equation 5-14 can be rewritten to incorporate the UWDS transition platform that can be solved as a multi objective optimisation problem subject to:

$$\min f_{cost}(\mathrm{U_j}) = \underset{X^P}{Min} \sum_{j} [f_{\cos t}(U^P, U_j^{\,T}) \qquad [5\text{-}15]$$

$$Minimize \qquad \sum_{P \in \beta} C^P L^P + \sum_{T \in \alpha} C^T L^T D^T \qquad [5\text{-}16]$$

Subject to the same constraints as in Equation 5-15, UWDS pipes and pipe cohorts remain fixed during the transition stages form the platform described by the vector U^P of pipes and pipe cohorts. Uj^T represents the variable pipes T of the UWDS transition platform. D^T is obtained from commercially available diameters (d_1,d_2,d_3,........,d_N); β and is a set of candidate pipes and pipe cohorts to be transitioned . L is the length of the UWDS pipes, CP are the conventional pipe and pipe cohort operation and maintenance unit costs and C^T is the cost of the transitioned pipes of the UWDS. The product C^T D^T could also be replaced by $1.1D^{T1.5}$ from (Savic and Walters 1997; Vairavamoorthy and Ali 2000).

Determination of PTIC involves several criteria SIC, TIC and OIC described in the previous sections. Solving this optimisation problem can be achieved based on either a single objective optimisation or a multi-objective. The single-objective optimisation process generates a single optimal solution whereas the multi-objective optimisation approach generates a set of noninferior pareto solutions (Savic et al. 2002). For this study, the multi objective problem was reformulated into a single objective problem by combining the different objectives using weights. The reformulation of the single objective was considered because the objectives have similar units and it was considered appropriate to combine them into one function, and its simplicity and ease of use. Thus, the mathematical representation of the optimisation problem for PTIC was reformulated to become a single objective problem by combining social, technical and operation and maintenance impact costs to analyse UWDS transition impact. The conventional transition platform is reformulated to include the consideration of socio-economic aspects. The modified UWDS transition platform problem can be stated as

$$Minimize\ PTIC = \frac{(1+\alpha)}{(1+r)^{tp}} * \left[W_{OIC} \sum_{P \in \beta} (LIC + BIC)_j{}^P + W_{TIC} \sum_{T=\sigma} C^T L^T D^T \right] \qquad [5\text{-}17]$$

Following Wei et al (2009), this problem can be solved as a two stage optimisation problem because it faces less computational load than the one stage optimisation approach. The first stage is Stage 1-Establish UWDS transition platform elements and the second stage is Stage 2-determine the components of the UWDS that are more suitable for transitioning in the future.

5.3.1 TIC and OIC Weights

The combination of the attributes of the PTIC requires weight that reflects their relative importance. Although weights for TIC and OIC can take many values, in this study equal weights were considered because of their simplicity. However, in real life weights can be generated based on expert interviews and comparison techniques such as an analytical hierarchy process introduced by Satty (1971). Details of the approach are elaborated in Chapter 3. However, this process has not been the focus of this chapter as what was required is to test the developed approach. Nonetheless, the sensitivity of the weights are analysed on both the Iganga and Rubaga case studies in Chapter 6 and 7 respectively.

5.4 Genetic Algorithms

Identification of the optimal constituents of the UWDS transition platform, herein called designing for UWDS transitionability, involves a combination of many pipes and pipe cohorts each of which has different choices. This therefore creates a large decision design space from which optimal decisions can be obtained through simplistic comparisons. To this extent, Genetic Algorithms have been used to aid in the identification of optimal solutions. The GA uses a two stage optimisation process to determine the components of the UWDS transition platform. A GA was implemented based on [Equation 5-17] which involved integrating the socio-economic impact indices of the UWDS pipes and pipe cohorts established in Chapter 3, EPANET, and the source UWDS and desired UWDS transition options. This process resulted in the identification of the PTIC of pipes and pipe cohorts as a surrogate for the cost of re-optimising an UWDS when a pipe or pipe cohort is retained in an UWDS.

A genetic algorithm is a search process through which a population of solutions to an optimisation problem is selected through natural genetic processes involving recombination, mutation, elimination or retention to achieve survival of the fittest population. Recently, GAs have demonstrated their superiority in determining optimal solutions for UWDS (Savic and Walters 1997; Vairavamoorthy and Ali 2000; Dandy and Engelhardt 2001). The merits of a GA are that they require no prior knowledge of how to solve the problem. However, these are criticised for the relatively high computation time associated with volume of computational load related to the need to carry out many simulations of the physical system (Dandy and Engelhardt 2001), and the GA does not guarantee that the solution obtained is the global optimum.

Although the optimisation of the PTIC can be implemented using either a simple GA or an advanced GA (NSGA-II) (Deb et al. 2002), in this study a simplistic GA was used to analyse the developed approach for designing for UWDS transitions. This is because it is suited for a simple objective optimisation problem. Secondly, it requires lesser computational effort and is easier to use when undertaking a parametric study to test the robustness of the proposed approach. On the other hand, the NSGA-II GA is more suited for multi-objective optimisation problem. The GA is currently used to solve many optimisation problems in the water sector.

5.5 Model Application to Hypothetical Case study

The UTIAM framework developed in Section 5.2.1 is applied to a hypothetical case study. The framework is implemented in a tool that links EPANET2 for hydraulic analysis (Rossman 2008) with a genetic algorithm optimizer using the Visual C++ to create a tool that determines the pipes and pipe cohorts of an UWDS that have the least impact on future UWDS. EPANET2 is a computer program developed by the United States Environmental Protection Agency that performs extended period simulation of water pipe networks. Fig 5-1 shows the algorithms of the developed methodology for the design for UWDS transitionability.

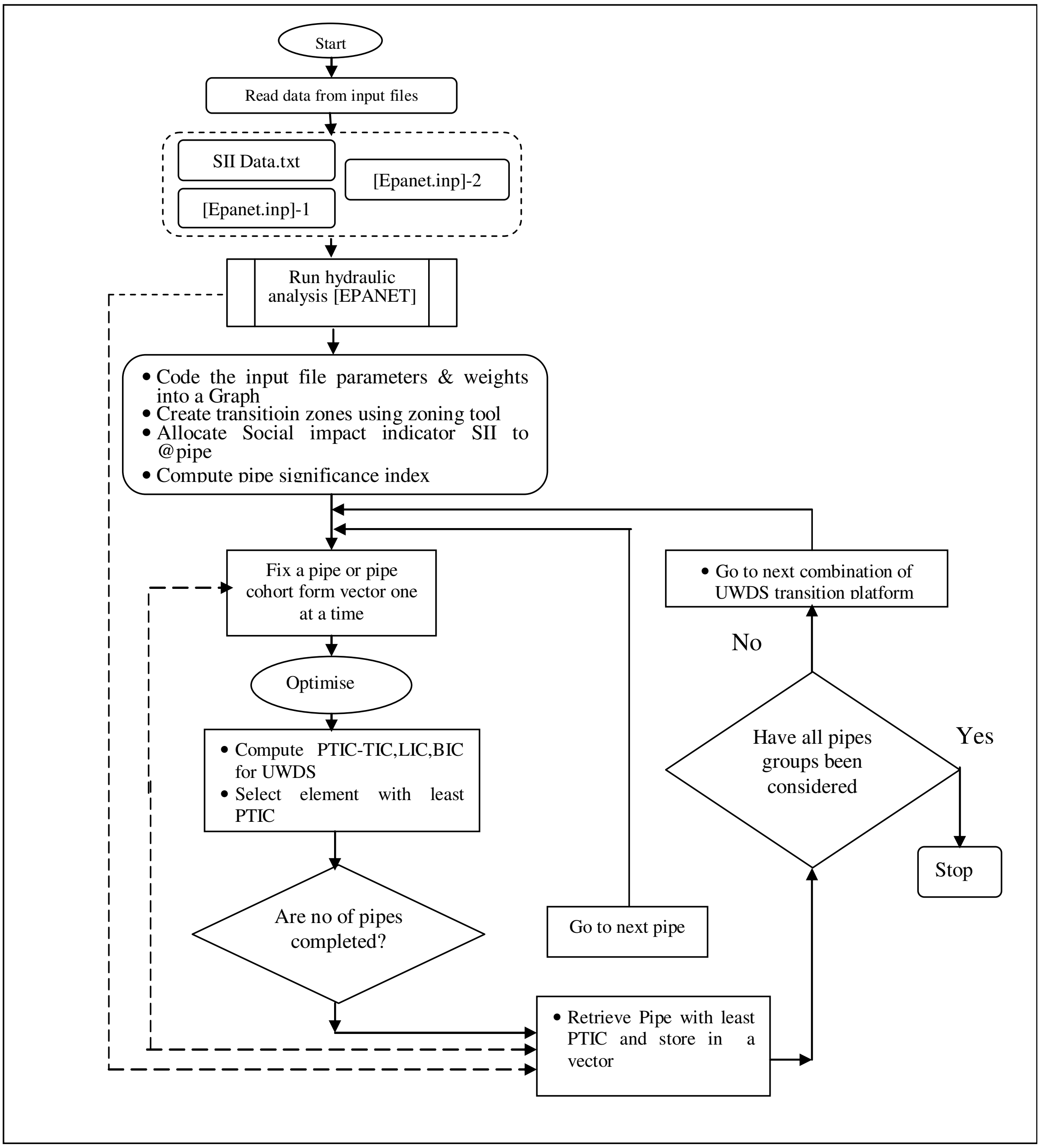


Figure 5-1: Proposed Pipe transition Impact assessment Algorithm

5.5.1 Back ground-Definition of the problem

The effectiveness of the approaches, frameworks and models developed in this chapter is demonstrated by application on a simple hypothetical case shown in Fig 5-3 (a). The case study aims to test the sensitivity and to examine the robustness of the developed approaches. Scenarios are suitable where the prediction of future events cannot be achieved with a degree of accuracy. The scenario approach for prediction of future events was also selected because it is applicable where there is limited statistical data and a probabilistic description of the future events.

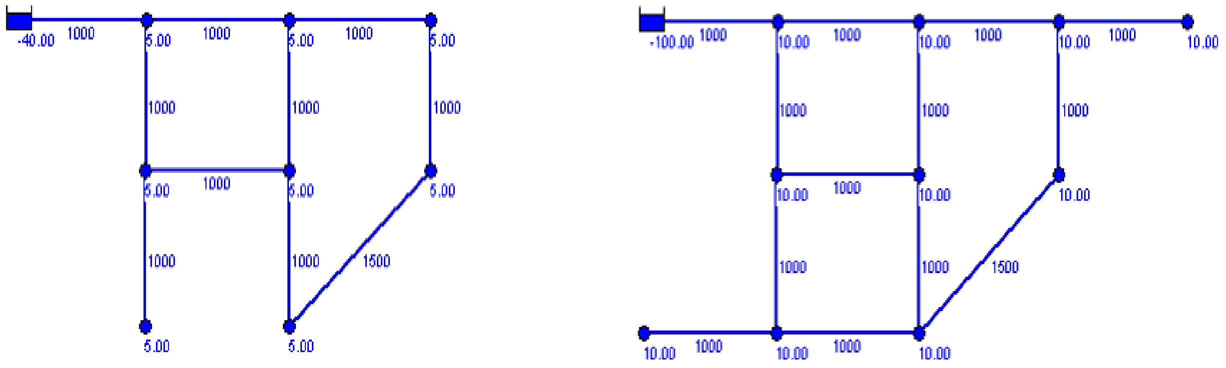
Based on anticipated future changes, cases to represent future transitions can be developed. The identification of the appropriate future scenario can be based on scenarios for the UK government foresight programme year (2000). To simulate realistic uncertainties of the UWDS, future scenarios for the UWDS are constructed. Based on these scenarios, long term strategies for the desired UWDS strategies are developed.

In the case study only the world markets scenario has been considered because it best represents the worst case scenario amongst all the scenarios for the UWDS. In this scenario, rapid population growth and urbanization is assumed to cause an increase in demand beyond the normal growth rates as shown in Table 5-1. Hence, the future uncertainties for the UWDS are presented by three hypothetical future UWDS transition scenarios shown in Figure 5-3 (b)-(d). A summary of the growth in demand, pipe length and the deterioration of the pipe roughness through the transition phases is presented in Table 5-1. Details of the characteristics of the existing UWDS and the other scenarios of the $\text{UWDS}_{1\text{-}3}$ can be found in the Appendix C. The hypothetical case study has one water tank with pipes increasing from 10 to 21 in three transition periods. During the same period the demand nodes increase from 8 to 15 while the demand increases from 40 to 300 litres.

Table 5-1: UWDS Transition scenarios

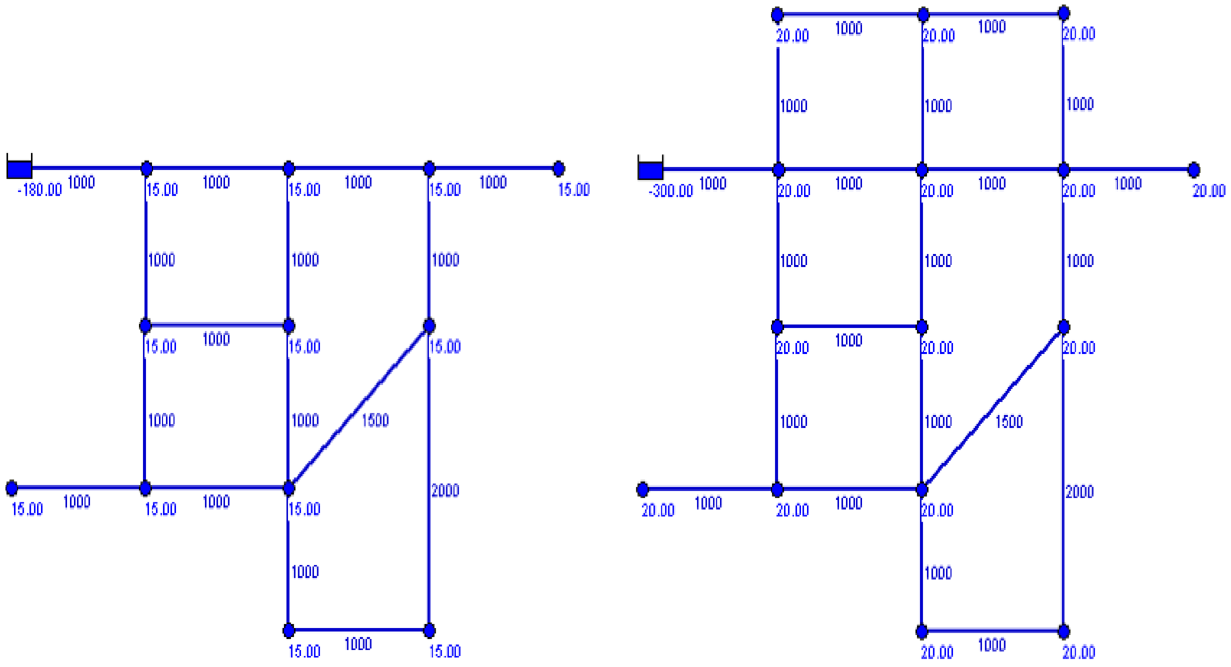
UWDS	Existing Fig 6-2 (a)	$UWDS_1$ Fig 6-2 (b)	$UWDS_2$ Fig 6-2 (c)	$UWDS_3$ Fig 6-2 (d)
Pipes (No)	10	13	16	21
Nodes (No)	8	10	12	15
Demand (Liters)	40	100	180	300
Hazen William Coefficient*	105	100	95	90
Length (m)	10500	13500	17500	22500
Transition period (tp)	0	5	15	25

*The Hazen-Williams coefficients presented in the Table 5-1 are those for the existing (and deteriorating) stock through the transition phases.



(a) -UWDS$_0$

(b) –UWDS$_1$



(c) –UWDS$_2$

(d) –UWDS$_3$

Figure 5-2: Scenarios for future UWDS [UWDS$_0$- UWDS$_3$]

Based on scenarios in Figure 5-2, the developed options for transitioning the hypothetical UWDS were analyse. The problem is that of determining the UWDS transition option that minimises future UWDS transition impacts. To test the options two hypothetical transition strategies for the future UWDS were created. A conventional approach- with the future system based on an existing system UWDS. UWDS transition platform approach -future system based on a totally new system UWDS. Computations of the social and technical impacts were carried out for both transitioning options. The results for the two scenarios were compared to check how robust the transition options were and how they impact the cost of transitioning the UWDS in the future.

5.5.2 Significance of Pipe based on PTIC vs. Pipe Significance Index (PSI)

From literature review, approaches for analysing pipe significance do not consider the significance of pipes with respect to socio-economic impacts and the impact of the pipe on the future transitionability of the UWDS. Hence, before applying the proposed transition approach it is desirable to assess whether ranking pipes based on pipe transition impact cost is significantly different from the conventional approach that ranks of the pipe based on its impact on pressure for the developed hypothetical future transition scenarios. For this purpose, the algorithm in [Equation 5-17] was developed and coded in the visual C++ programming language. Since existing pipe upgrade functions are skewed to technical cost, socio-economic costs and impacts are quantified in PTIC. The PSI by (Arulraj and Rao 1995) is used to represent the conventional approach for ranking pipes based on pipe pressure. Results of the comparison are shown Table 5-2 and Figure 5-3.

Table 5-2: Comparison of pipe rank based of PTIC Vs PSI

Pipe no	PSI	UWDS$_0$ to UWDS$_1$	UWDS$_2$	UWDS$_3$	Mean PTIC (£)	Standardized PTIC	Standardized PSI
1	1.65	2,251,775	7,321,896	5,534,976	5,036,216	1.00	1.00
2	1.28	1,998,135	4,904,990	3,564,270	3,489,132	0.69	0.78
3	1.26	2,415,370	4,751,870	3,131,630	3,432,957	0.68	0.76
4	1.32	2,440,600	4,658,590	3,329,100	3,476,097	0.69	0.80
5	1.08	2,407,870	5,208,260	3,905,070	3,840,400	0.76	0.65
6	1.23	2,542,475	6,101,580	4,612,480	4,418,845	0.88	0.74
7	1.20	2,155,490	5,484,370	3,617,640	3,752,500	0.75	0.73
8	1.17	2,611,445	4,862,200	2,568,580	3,347,408	0.66	0.71
9	1.29	2,453,305	5,378,350	4,144,090	3,991,915	0.79	0.78
10	1.16	3,052,355	5,433,310	3,986,150	4,157,272	0.83	0.70

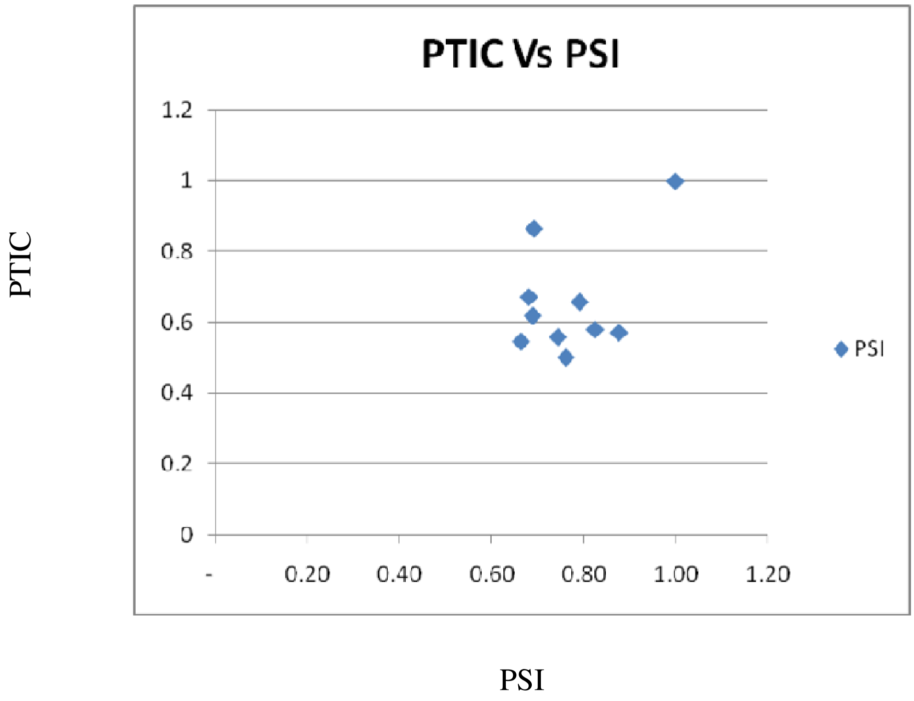


Figure 5-3: Standardised PTIC Vs PSI

From the above plot, there is no correlation between ranking pipes according to PTIC and ranking pipes according to PSI. Using PTIC to rank UWDS pipes and pipe cohorts gives different results from that of PSI. Hence, PTIC can be adopted as criteria for analysing plausibility of pipes and pipe cohorts for UWDS transitions. To identify the cohort of pipes that can be retained in the present UWDS, the net impact of the individual pipes is modelled to establish the platform of pipes that will have the least impact on the present and future transition of UWDS.

5.5.3 Application of the developed approaches for the identification of Pipes and pipe cohorts for UWDS Transitions

Two approaches can be used to identify pipes and pie cohorts for UWDS transitions. Prioritization models- that establish the criticality of an UWDS pipe based on its significance derived from its impact on future UWDS transitions pipe significance, and a two stage optimisation models that follow the product platform concept (Wei et al. 2008). The merits and demerits of these approaches have been elaborated in Chapter 2. In this study both methods are applied on the hypothetical case study. The application of the two approaches to determine the pipes and pipe cohorts of the hypothetical case study to transition are elaborated in Sections 5.5.4 and 5.5.5.

5.5.4 Determination of pipes to transition based on pipe prioritisation models

This approach was implemented on the hypothetical case study to prioritize pipes and pipe cohorts for upgrading based on their impact on future UWDS transitions. A plot of PTIC vs SIC was used to identify a group of pipes and pipe cohorts with the least impact on UWDS transitions. A Conceptual decision framework was imposed on the graph to identify priorities of pies and pipe cohorts. The classification of the transition criticality follows the pipe prioritization decision models that plot pipe condition against significance in technical literature for rehabilitation of pipes (Engelhardt et al. 2000; Lippai and Wright 2005). Similarly in this model pipe condition is replaced by PTIC while significance is measured in terms of SIC. Details of the results are shown in Figure 5-4. The classification of very low, low, moderate and high rehabilitation priority are replaced with very low, low, moderate and high transition priority

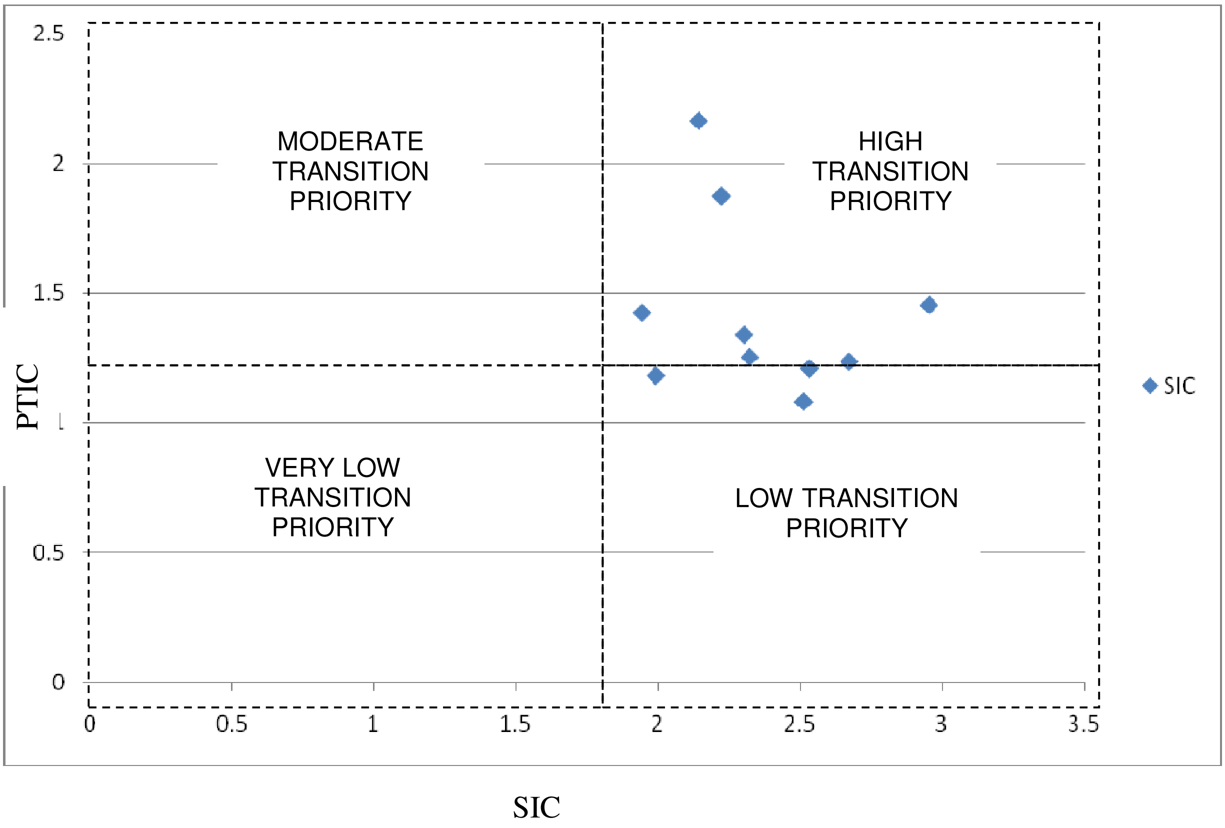


Figure 5-4: Prioritization of UWDS transition criticality based on PTIC and SIC

From Figure 5-5, 50% of the pipes of the hypothetical network can be broadly classified to have low transition priority whereas the others have required high transition priority. This confirms that prioritisation of pipes based on UWDS transition pipe criticality is a suitable approach for identifying pipes and pipe cohorts for transitioning.

5.5.5 Determination of pipes to transition based on optimisation models

The determination of pipes to transition using optimisation models has been based on the UWDS transition platform concept. The sequence (rank) of the pipes to include in the UWDS transition platform was identified following the two stage approach presented by Wei et al. (2009). The first stage involves the identification of elements of the incumbent UWDS that have the least impact (technical and social) on future transitionability of the system. Pipes and pipe cohorts of the UWDS transition platform with the least impact on the future were identified using PTIC as a surrogate for the pipe impact transition cost. PTIC costs include TIC, SIC and LIC and BIC and were analysed using Equation 5-17. PTIC was obtained from the derivative of the cost of re-optimising pipes and pipe cohorts of the incumbent UWDS that is composed of a platform of pipe stock of an incumbent. Based on PTIC, the UWDS pipes and pipe cohorts are ranked in ascending order. The pipe with the lowest PTIC is selected as the first pipe that of the UWDS transition platform. The sequence of the pipes and pipe cohorts and their respective PTIC obtained for the hypothetical case study are presented in Table 5-3.

Table 5-3: PTIC for the different pipes and pipe cohorts of the UWDS transition platform

UWDS Transition platform	PTIC		
	$UWDS_1$	$UWDS_2$	$UWDS_3$
4	2.00	2.88	4.86
4-7	1.85	2.48	4.54
4-7-5	1.67	2.31	4.37
4-7-5-8	1.83	2.79	3.94
4-7-5-8-6	1.85	2.87	4.03

SIC were modelled in the PTIC derived from SII factors shown in Table 5-4. For the hypothetical case, SII have been hypothetically developed, however details of how they can be derived for a real case network can be found in Chapter 3.

Table 5-4: Pipe Age and Socio-economic impact cost factors

No	*Pipe ID*	*SII*	*Age*
1	2	0.8	25
2	3	0.8	20
3	4	0.75	20
4	5	0.7	25
5	7	0.7	22
6	8	0.65	10
7	9	0.65	15
8	10	0.5	18
9	12	0.5	25
10	13	0.7	17

The approach described in the Section 5.5.5.1 was followed

5.5.5.1 Details and results of the proposed approach for prioritisation of pipes for the UWDS transition platform

The method proposed in this chapter is based on the concept that UWDS pipes and pipe cohorts of an incumbent UWDS have varying degrees of importance based on their hydraulic and socio-economic impact on the future UWDS. For example, transitioning a pipe is a highly developed area or near the source would attract greater socio-economic and technical (hydraulic) impact than transitioning a pipe located in an undeveloped area further away from the source. If pipes and pipe cohorts can be ranked based on their impacts (PTIC), then this information can be used to develop a method to identify optimal components of an UWDS transition platform. In particular, the information can be used to eliminate pipes with a relatively higher impact on the transitionability of the future UWDS. The method used to identify the priorities of pipes in an UWDS transition platform involved the following steps:

a) The first step is to establish the incumbent and optimised UWDS
b) The second step is to identify the relative importance of all pipes of the incumbent UWDS based on their impact on the technical(hydraulic) and socio-economic impact on the future UWDS. In this step pipes are analysed and a PTIC is computed using equation 5-17. PTIC is a surrogate for the pipe impact transition cost with respect to the future UWDS. A PTIC vector is constructed where pipes of the incumbent UWDS are ranked based on their PTIC. The pipe with the least PTIC is then identified as the first element and stored in a vector that contains pipes of the UWDS transition platform; and
c) The final step identifies the pipes and pipe cohorts of the UWDS transition platform which are stored in the vector. This process continues until the optimal number of pipes with the least impact on the future transitionability of the UWDS is identified. The algorithm is terminated when the GA optimisation no longer produces any off spring due to relatively high transition impact costs.

5.5.5.2 Results discussion for prioritisation of pipes for the UWDS transition platform

Based on the above process, Pipe 4 was identified to have the least impact on the future UWDS. Pipe 4 is placed in the vector of pipes of the UWDS transition platform and step (b) is repeated. Again all pipes are analysed and PTIC is computed with respect to the first identified pipe and then the next pipe to constitute the platform is identified. . The next pipe identified in the second round was 7 and that for the third round was 5. This process was repeated until the GA no longer produced off spring due to relatively high transition impact costs. Based on the aforementioned process, the sequence and PTIC of the hypothetical case study is presented in Figure 5-5.

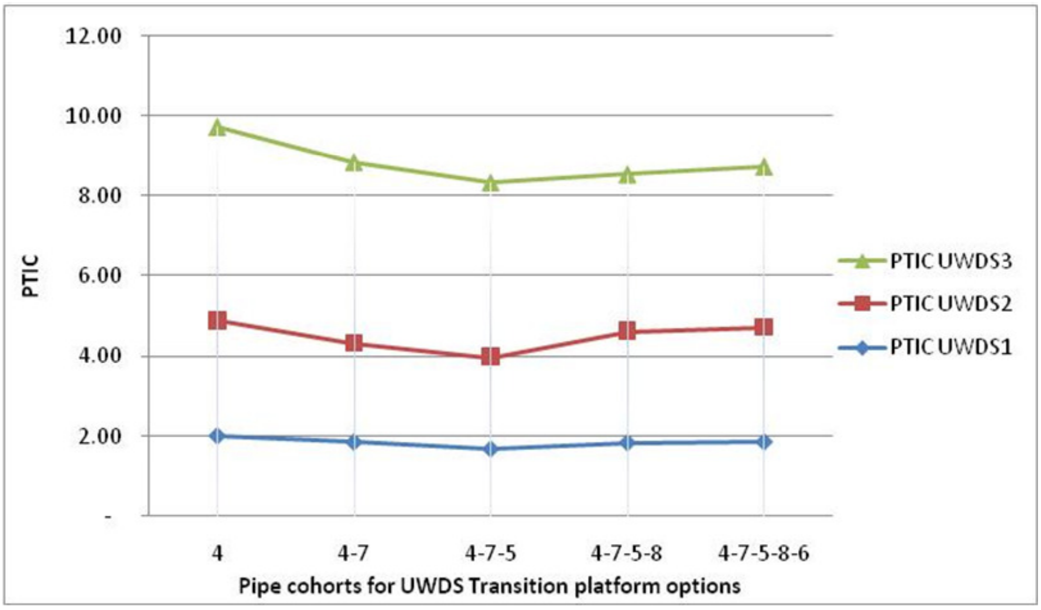
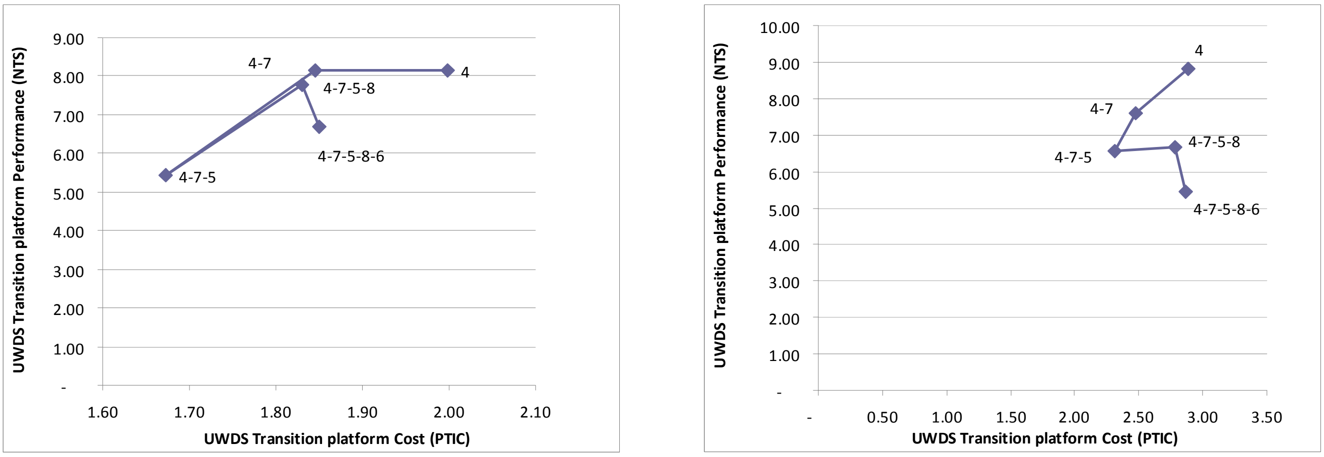


Figure 5-5: PTIC for pipe(s) retained

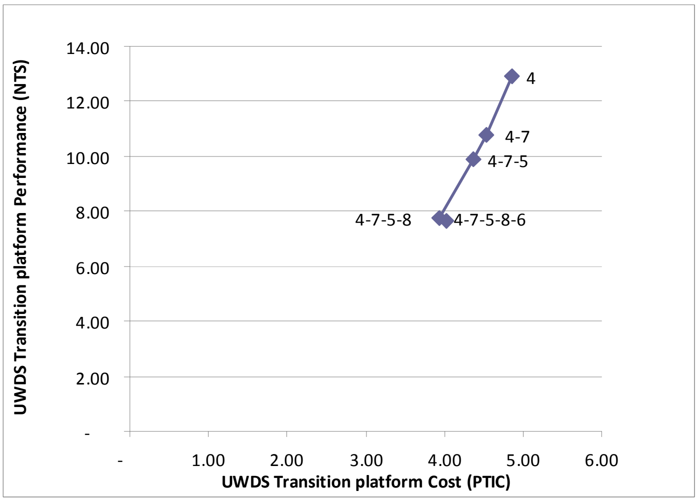
From Figure 5-5 it is observed that there are five feasible platform options i.e. a platform with 1, 2,3,4,5 elements corresponding to pipe cohorts 4, 4-7, 4-7-5, 4-7-5-8 and 4-7-5-8-6 that can be retained in the future UWDS at minimal cost. Hence, only 5 pipes (4, 7, 5, 8, and 6) of the original network can be retained in the future system.

However, the prioritisation of pipes based on purely PTIC can be misleading as the performance of the future UWDS is affected as well. Hence, the performance of the UWDS transition platform options was analysed in addition to the PTIC. In this study, the performance of the five transition platforms options for the three transition phases UWDS1, UWDS2, UWDS3 was measured using NTS. NTS is in effect the ratio of the hydraulic performance of the present UWDS to that of the optimised future UWDS. NTS was computed based on resilience index formulation presented in Equation 5-1 and the results of the evaluation of the performance of the UWDS platform options under the aforementioned three transition phases is presented in Figure 5-6 (a)-(c). The figures represent how the PTIC of the UWDS transition options varies with the performance for the three UWDS transition phases. The points in the graphs represent the UWDS transition options with 1, 2, 3, 4 and 5 pipe platform elements. These were obtained following the approach described in Section 5.5.5.1 and 5.2.1.1.



(a) Transition phase 1-UWDS$_1$

(b) Transition phase 1-UWDS$_2$



(c) Transition phase 1-UWDS$_3$

Figure 5-6: PTIC Vs Performance for the UWDS Transition options (NTS)

As mentioned in Section 5.2.1.1, pipes have varying impacts on an UWDS when retained or transitioned in an UWDS e.g. Pipe 4 has the least PTIC on the transitioning of the incumbent UWDS to the future. PTIC drops starting with pipe 4 and begins increasing after pipe cohort 4-7-5. This is because sharing pipes and pipe cohort's between the present and the future UWDS reduces the costs on the future UWDS for the first three platforms. As shown, whilst the cost of the UWDS transition platform drops with an increase in the number of pipes and pipe cohorts retained the performance reduces as well. This is observed by the reduction in NTS as the number of pipes platform elements increase (Figure 5-6 (a) –(c)). The reduction in performance is due to the increase in the impact of the hydraulic characteristics of the incumbent pipes on the future UWDS.

After the third UWDS transition platform, PTIC increases with an increase in platform elements. This is observed after the platform 4-7-5 in (Figure5-6 (a) and (c)). When pipe 8 and 6 are added to the pipe cohort 4-7-5, there is a rapid increase in PTIC. This is the point beyond which the platform of the hypothetical UWDS causes lock-in. According to Unruh (2000) lock-in occurs when the benefit of transitioning is less than the cost of transitioning. Hence to limit the impact of the incumbent elements on the performance of desired future system, only a limited number of elements of the incumbent UWDS can be retained in the desired future UWDS. This ensures that the platform does not cause lock-in.

For the hypothetical case study, only five platforms options with 1, 2,3,4,5 elements corresponding to pipe cohorts 4, 4-7, 4-7-5, 4-7-5-8 and 4-7-5-8-6 of the original network can be retained in the future system at minimum cost and maximum performance. The hypothetical case has demonstrated that prioritisation of pipes based on a two stage optimisation approach is a suitable method for identifying pipes and pipe cohorts of the incumbent UWDS that have the least impact on the future transitionability of the UWDS.

5.6 Evaluation -Comparison and Selection of the UWDS Transition Option

In this section, two UWDS transition options created and compared are conventional approach- with the future system based on an existing system and UWDS transition approach based on the UWDS transition platform developed in Section 5.3.5. This approach aspires to transition the existing UWDS to a desired future UWDS based on a totally new system hinged around UWDS transition platform.

PTIC was used to analyse the UWDS transition options those that quantify the technical impacts, and those that quantify the operation and maintenance impacts. The socio-economic impacts were modelled in the PTIC as SIC factors. For simplicity and demonstration purposes, equal weights were assumed for the different components of PTIC. Evaluations of the transition options should not only be based on the developed metrics. Therefore, additional metrics can be developed for further in-depth analysis of the transition options. The developed transition scenarios of $UWDS_{1-3}$ provide an assessment of the pros and cons of the different transition options. The results of the evaluation of the existing UWDS and their transition on the path to the three transition options show significant differences in the terms that constitute the PTIC.

PTIC were estimated from a total of SIC, TIC, LIC and BIC represented by Equation 5-17. TIC and OIC was analysed using a tool that links Visual C++ and EPANET2 software to perform hydraulic simulations of the UWDS during the transition process. The permissible means allowed for transitioning the UWDS were the replacement of existing pipes with new pipes of equal or larger diameters. The unit costs for pipe replacement were those obtained from multiple industries the biggest supplier of ISO approved pipes in Uganda (Multiple Industries 2012). TIC was computed from the cost for re-optimising the UWDS when a pipe or pipe cohort is retained in the UWDS. During the re-optimisation process the cost permitted was the price at 2012 for replacing existing pipes with new pipes of equal or larger diameters. LIC was estimated from Equation 5-10 in which the costs of leakage due to pipes and pipe cohorts of the hypothetical UWDS transition platform were obtained. BIC was estimated from Equation 5-12 from which the cost of repairing bursts caused by pipes and pipe cohorts retained in the hypothetical UWDS. The rate of pipe bursts for the hypothetical case study was assumed to be 41/100km/year (Mutikanga 2012) and the burst unit cost 1038 £/burst based on (Awad et al. 2008).The Leakage unit cost was estimated to be 2.2 £/m3, based on the unit cost a customer pays per m3 of water used (Awad et al. 2008). The Hazen-Williams coefficients for the existing (and deteriorating) stock through the transition phases were generated based on scenario analysis and are presented in the Table 5-1. The PSI was estimated based on (Arulraj and Rao 1995) and SII was computed from the approach development of SII developed in Chapter 3. The impact of transition options was based on the analysis of the three future transition options based on quantification of PTIC. The results of the analysis and comparison between the two transition options are presented in Table 5-5 and summarised in Fig 5-8.

5.6.1 Quantification of future PTIC and life cycle costs

In the computation of UWDS transition impact life cycle costs, PTIC for the first phase is the present value while that for the second and third phase are in the future. Thus a cash flow discounting method is used to convert all PTIC during the transition phase to the present worth of the initial year of analysis. The present worth (PW) converts all the PTIC during the transition phase to their equivalent value in the first phase of the transition period. The PW of a future worth of an amount (FW) at a discount rate of r% over a transition period *tp* is obtained from

$$PW = FW \frac{1}{(1+r)^{tp}} \qquad [5\text{-}18]$$

The UWDS transition impact life cycle cost in Table 5-5 are obtained by adding discounted PTIC for each phase using Equation 5-17 and 5-18. The set back with discounting is how to choose an appropriate discount rate. A conservative bank of England discount rate of 3.5% has been assumed. While the assumed rate can be contested for favouring the high capital spending for the more transitionable option, it is argued that the computations are auditable and ensure some degree of transparency. Another merit is that the approach makes the comparison of the PTIC lifecycle costs directly relatable. The results of the PTIC comparisons for the hypothetical case are presented in Table 5-5. Sensitivity analysis was therefore carried to analyse the impact discount rate on the PTIC.

Table 5-5: Lifecycle PTIC of Conventional Transition Approach Vs UWDS Transition platform approach

Pipe Index	Original UWDS	Conventional approach Based on an Exixting System						Conventional Transition without UWDS Transition Platform						UWDS Transition Platform Based on a new system					
		Diameter			PTIC			Diameter			PTIC			Diameter			PTIC		
		SC1	SC2	SC3	SC1	SC2	SC3	SC1	SC2	SC3	SC1	SC2	SC3	SC1	SC2	SC3	SC1	SC2	SC3
1	356	356	356	356	-	-	-	-	762	762	68	461,662	-	406	-	-	202,329	-	-
2	152	152	152	152	-	-	-	406	305	762	225,769	113,691	248,368	609	-	-	357,324	-	-
3	152	152	152	152	-	-	-	762	762	356	422,115	-	91,653	508	-	-	241,572	-	-
4	203	203	203	203	-	-	-	-	-	-	2,422	1,740	199	-	-	762	9,186	6,512	260,520
5	50	50	50	50	-	-	-	-	-	-	9,124	718	4,773	-	305	-	3,963	64,995	1,992
6	152	152	152	152	-	-	-	-	-	254	1,486	18	57,869	762	609	-	358,597	188,306	-
7	90	90	90	90	-	-	-	-	-	-	7,326	5,241	5,260	-	-	508	8,458	5,996	142,297
8	152	152	152	152	-	-	-	-	-	457	3,130	3,899	100,652	356	90	-	118,162	24,961	-
9	254	254	254	254	-	-	-	-	508	508	561	174,124	-	508	-	-	216,352	-	-
10	100	100	100	100	-	-	-	406	457	609	151,660	131,779	154,741	508	-	-	236,528	-	-
11		*	*	*	*	*	*	609	457	356	231,021	123,071	58,774	125	305	203	36,215	-	-
12		*	*	*	*	*	*	305	406	203	107,562	106,519	29,656	203	203	356	54,793	-	52,227
13		*	*	*	*	*	*	110	203	80	38,385	59,264	25,307	254	457	406	72,121	133,785	89,325
14			*	*		*	*		203	305		51,443	55,914		305	203		71,044	32,503
15			*	*		*	*		305	508		137,425	166,717		457	508		212,887	-
16			*	*		*	*		90	203		25,666	31,074		60	406		20,888	66,558
17				*			*			305			50,226			305		-	47,332
18				*			*			50			17,969			100		-	16,111
19				*			*			100			20,796			152		-	18,690
20				*			*			609			135,227			508		-	106,781
21				*			*			508			120,039			50		-	87,650
Total UWDS transition costs#											1,200,628	1,396,260	1,375,213				1,915,601	729,373	921,986
UWDS Life cycle transition impact cost													3,972,101						3,566,960

* PTIC and optimal diameter could not be ascertained by model due to failure to meet minimum hydraulic constraints

- means that the diameter remains unchanged during the UWDS transition process

SC1-UWDS network for Scenario1-UWDS$_1$; SC2-UWDS network for Scenario2-UWDS$_2$; SC3-UWDS network for Scenario1-UWDS$_3$

[#] Note: The UWDS transition costs in the table are discounted to the initial year of UWDS Transition

- Discount Rate used for the time value for money is 3.5%

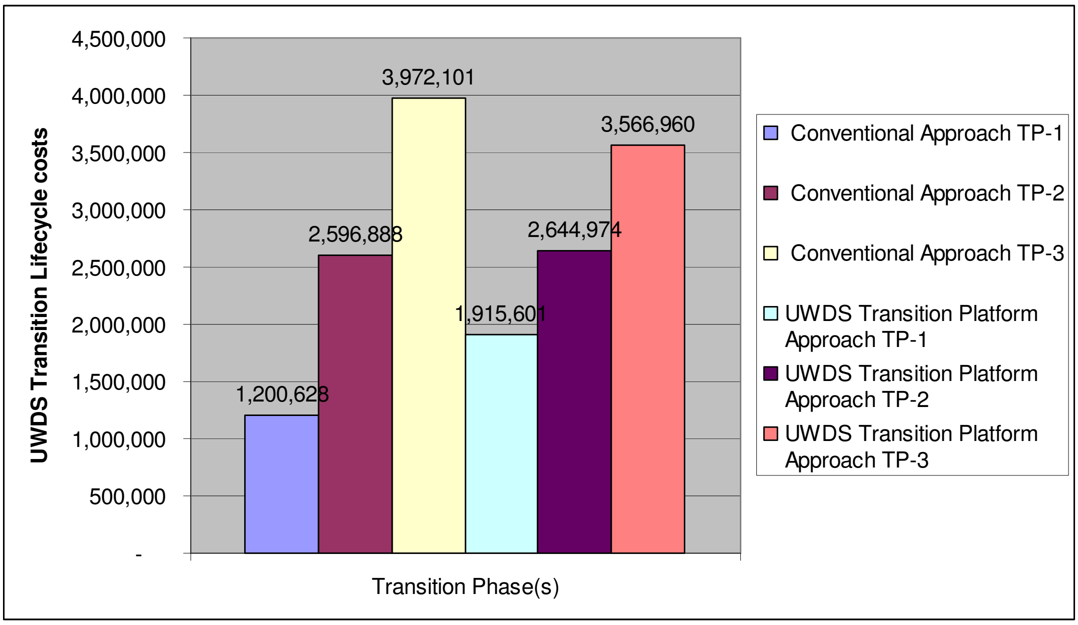


Figure 5-7: UWDS transition lifecycle costs for the three UWDS transition phases (discounted to the present using a discount rate of 3.5%)

The sensitivity of PTIC to change in discount rate was investigated by changing the discount rate by, 10%, 20%, 50% and 100%. The results of the variation of PTIC with changing discount rate are presented in Figure 5-8.

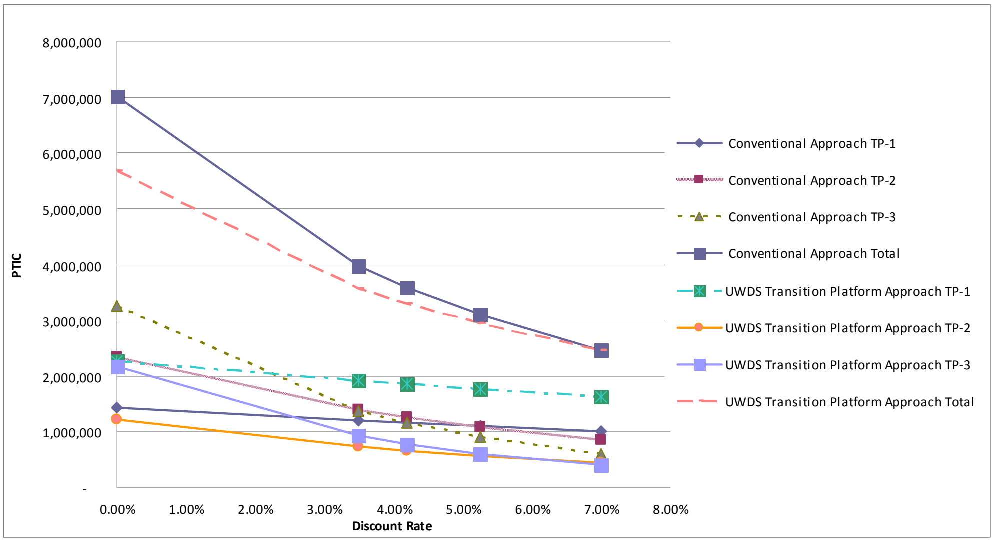


Figure 5-8: PTIC variation with discount rate

5.7 Results Discussion

The transition impact costs for the design that is based on the existing UWDS, the design that does not consider future transitionability and one that is based on the UWDS transition platform are not feasible, 1,200,628 and 1,915,601 respectively. So the UWDS transition platform requires relatively higher PTIC than that for transitioning without considering an UWDS transition. The higher initial cost of 1,915,601 is due to the higher initial capital investment cost required to make the UWDS transitionable in the future. Although the initial lifecycle cost for upgrading an UWDS without considering transitionability (1,200,628) is lower than the cost for upgrading an UWDS based on the UWDS transition platform (1,915,601), the UWDS transition impact life cycle costs are higher as shown in Figure 5-7.

A study of the sensitivity of the model indicates that PTIC follows a logarithmic decay trend with increasing discount rates. The smaller the discount rates, the higher the PTIC and cost saving observed between the conventional and the UWDS platform transition option. The total cost savings reduced from 19%, to 10%, 8%, 5% and 0% with an increase in discount rate of 10%, 20%, 50% and 100% respectively. In this hypothetical case study, the curve for the life cycle costs for the conventional and platform UWDS transition option intersect at a discount rate of about 7%. This means that no cost savings are realised when the discount rate exceeds 7%. After this point, though the hydraulic performance of the UWDS is improved, the PTIC for the UWDS transition platform option is larger than that for the conventional option. Hence while the assumed discount rate of 3.5% enables a cost saving of 10%, increasing this discount rate is less favourable for the more transitionable UWDS option.

The reduction in cost savings between the two transition options is potentially due to the fact that UWDS transition platform approach reduces costs for switching between the UWDS options. In turn this reduces costs due to impacts of pipes and pipe cohorts on future transitions. This is consistent with literature on product platforms that demonstrates the capability of the concept to reduce cost and performance when developing products within an uncertain environment Liu et al (2010). Using the UWDS platform enables early elimination of components that are likely to cause relatively large transition costs and impacts. This is demonstrated by the fact that upgrading an UWDS based on an existing system could not be achieved due to the failure of the optimiser to obtain feasible solutions due to technological lock in. Transitions between the three different phases based on the UWDS transition platform make the UWDS less expensive to transition through lower life cycle PTIC. Hence transitioning an UWDS based on the transition platform concept is more efficient and effective and is therefore recommended as a suitable approach for transitioning UWDS.

CHAPTER SIX

CASE STUDY–I: NWSC IGANGA WATER DISTRIBUTION NETWORK

6. Introduction

The effectiveness of the developed approaches, frameworks and models is also demonstrated by application on a case study in Iganga water service area (I-UWDS). The case study is selected for three reasons. This included the system with available information on how it has transitioned in tandem with the growth of the town from a town board to a municipality, being an emerging small town in a developing country whose urban planning, infrastructure and institutions are in early stages of development, and being one of the branches in NWSC making it possible to adopt data and parameters from other NWSC areas in case of missing data. The Town Central Distribution Zone, one of the three discrete networks of I-UWDS was chosen as specific study area because it constitutes the original network constructed in 1960 from which the present network has grown, and it could hydraulically be isolated with minimum impact to the existing system.

The case study is implemented on two fronts. They include descriptive/qualitative analysis, based on transition theory to ascertain the current state, identify the driver's barriers, opportunities and limitations for transitioning, and quantitative case study application to test the sensitivity and examine the robustness of the developed approaches. Based on the case studies the optimal strategy for transitioning the I-UWDS is recommended.

The study aimed to examine how the theory, the approach frameworks and models developed in Chapter 2 to 5 fulfil their objective. To test the sensitivity of the parameters and weights used before applying them to the case study of Kampala and to increase the evidence base of the suitability of the proposed approaches.

I-UWDS is one of the branches of NWSC located in Iganga Municipal Council one of the third largest towns in the Eastern Uganda about 120 km from Kampala, on the Kampala-Nairobi main road. The population for the service area is estimated at 100,000 with a growth rate of 4.86% per annum (UBOS 2011). The town is supplied by water from Lake Victoria pumped approximately 34 km from Jinja and has a distribution network that has grown from 5.34 km in 1960 to the current 54km. (Habitant Consultatnts 1994; NWSC 2010; BKS Global and Kagga and Partners 2012). In terms of the transition stages of urban water management, Iganga Municipal Council can be categorized as an early form of a 'water supply city' where only water supply is adequately developed with conventional treatment and distribution system.

Figure 6-1: Location of Iganga Municipal Council: located in Iganga district

This chapter is structured in four sections. Section 6.1 introduces and gives a brief overview of the approach for testing the proof of concept on a real case study in Iganga. Section 6.2 describes the Iganga study area. Section 6.3 describes the steps data, variables and methodology used in application of the approach for design for UWDS transitions on the case study. Finally, the sensitivity of the model is tested in Section 6.4.

6.1 The Study Area

The I-UWDS is located in Iganga Municipal Council; the third largest town in the Eastern Uganda and the main administrative and commercial capital of Iganga District. The Municipality lies in the east and northeast of Uganda at 00 36 54N, 33 29 06E. Iganga lies within the Lake Victoria climatic zone and receives a fairly well distributed precipitation over the year which is on average 1,279 mm per year. The town is among the 23 towns managed by National Water and Sewerage Corporation (NWSC). NWSC was established in 1972 as an autonomous public utility with the objective of supplying water and sewerage services to large urban centres in Uganda (NWSC 2010). The total length of I-UWDS is 54 km and covers the municipality and the neighbouring suburbs in the Church Missionary Society Area (CMS) area, Bulanga area and the Musiita area which are located 3, 9 and 12 km respectively from the municipality.

The municipality is a case that represents the pressures faced by an emerging town in a developing country with a conventional UWDS that is under pressures to transition due to the high population growth rates, urbanisation and mature infrastructure. Characterised by high urbanisation and population growth rates, the municipality has grown from a mere town to a municipality.

The water coverage in the area is estimated at 40%, with about only 40,000 people having access to piped water supply. With the projected population size of 170,000 by 2032, coupled with an aggravated high influx of the day time population, means that the existing I-UWDS will not be able to meet the demand. In addition it is expected change pressures such as the deteriorating infrastructure and urbanisation will escalate the demand for water supply and sanitation. The sewerage network is inadequate as it covers only 7% of the central business district. The area has 4 km of sewage network which collects and delivers sewage to two sewerage treatment plant (STP) located at Igamba in the western part and Nakavule STP in the eastern part of the municipality. Because the institutions operate in silos with NWSC being in charge of the water and sewerage system and the Iganga Municipal Council being in charge of the urban drainage and solid waste, there exist institutional barriers to the uptake of UWDS transitions.

The transition of I-UWDS commenced in the 1960s, when the first water supply system for the two was constructed to provide water to a growing town on a trade route that links Uganda as a land locked country to the port of Mombasa through Nairobi, Kenya. The transition has been underpinned by the formation of the UWDS transition structures at the social, institutional and technological level, and global change pressures. The transition of I-UWDS social, institutional and technological structures originates from the National Water Policy developed by the Government of Uganda in 1999. This led to Government of Uganda (GoU) to form studies and reform structures such as Rural Water Supply and Sanitation and the Urban Water Supply and Sanitation to guide the transition of UWDS. One such study is the Rural Towns Water Supply and Sanitation Study (RTWSS) undertaken by The African Development bank and The GOU aimed to aid the process of transitioning UWDS for towns such as Iganga (Habitant Consultatnts

1994) RTWSS aided the development of the institutional structure by transferring the management of the water system from the water board to NWSC. This opened the I-UWDS management to the NWSC institutional and technical structures in tandem with these changed managerial requirements (NWSC Act of 2000).

The other factor that influenced the development of new structures was the rapid urbanization and population growth that had outstripped UWDS of their capacity to meet the levels of service of UWDS. Global change pressures in the last two decades have resulted in significant changes in the UWDS for Iganga. As noted in Chapter 2, population dynamics influence transitions of UWDS. The population of the Iganga as supplied by I-UWDS grew by 94,000 people from 6,000 to 100,000 between 1969 -2012 (Habitant Consultatnts 1994; UBOS 2002; BKS Global and Kagga and Partners 2012). The growth rate between 1969-1991 was 4.5%, increasing to 6.5% between 1980-1990 (Habitant Consultatnts 1994). Population increase in Iganga Municipal Council is responsible for the increased water demand. Hence, there is pressure to transition in order for Iganga I-UWDS to meet the increased demand. To meet the increase in population and urbanisation, the original I-UWDS has transitioned into the existing UWDS transitioned into the existing UWDS (See Figure 6-2).

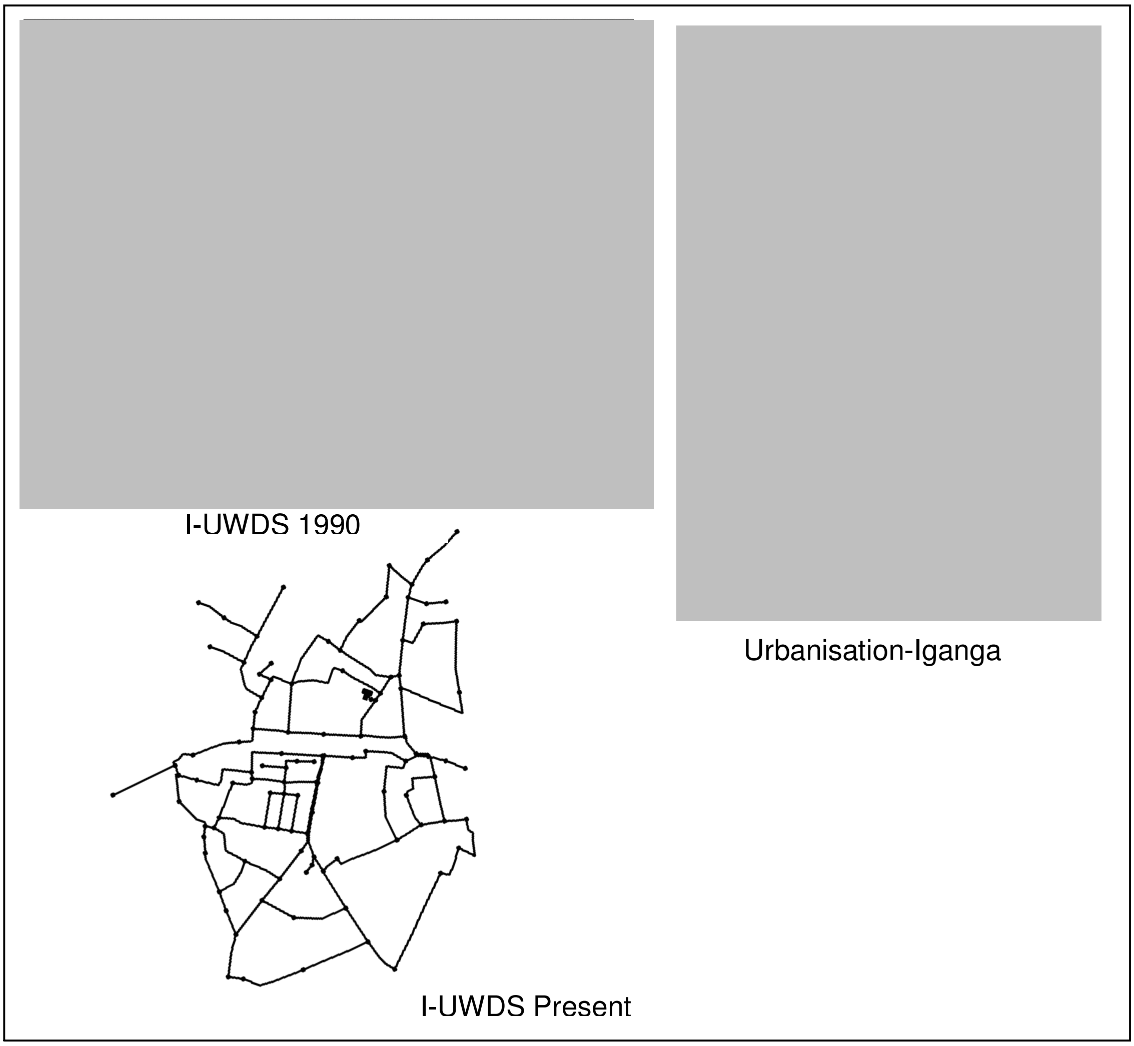


Figure 6-2: Transition of Iganga-I-UWDS [1990-Todate]

The existing I-UWDS is also characterised by high economic, social and environmental inertia that inhibits the transition of the existing system to its desired future state. A discussion with the area Manager NWSC indicates that the utility plans to transition the existing UWDS due to the "small size water mains" such as the upgrade of the 400m distribution mains along Bukyabubi road from DN40mm to DN80mm and many more. (NWSC 2012). However legacy infrastructure that causes high UWDS transition costs and impacts limiting future transitions. Moreover, these investments have been outpaced by the rapid population growth and urbanisation, resulting in water shortages and low pressures in most parts of distribution system. At present there are utility plans to increase the capacity of Bulanga and CMS reservoirs to 250m^3 each.

Though the case study is I-UWDS, only the Town Central Distribution Zone (TCDZ) a specific study area within Iganga was selected for application of the model. TCDZ was considered because it was possible to hydraulically isolate it from the entire network without affecting the hydraulic characteristics of I-UWDS. Secondly, TCDZ was selected because it constitutes part of the original network from which the present day network has transitioned. In fact TCDZ is one of the three original discrete water supply systems designed in 1960 to supply the town centre, the hospital and police. The TCDZ has grown from a pipe network of 5.73km length to the present 54km. The TCDZ is supplied by gravity from a storage tank located in the town centre. TCDZ has the following characteristics:

(a) A water storage tank that supplies the area by gravity.
(b) 54km pipe work with sizes that range between 40-450mm diameters.
(c) Supply zone elevation of between 1138-1186m.
(d) UWDS average pressure of 15.00m.

Few efforts have been made to transition the system in tandem with rapid urbanisation and population growth. However, the transitions have been driven reactive trial and error approach leading to a complex bandaged spaghetti network that is locked in an unsustainable form. The existing UWDS transitions have not kept pace with population growth resulting in water shortages and low pressures in most parts of distribution system. According to the Habitant

Consultants (1994), TCDZ is one of the areas that continue to be complained of intermittent water supply and dry zones. The need to determine the optimal approach for transitioning the I-UWD is due to the need to transition the existing UWDS without constraining future transitions. Under such circumstances, the assessment of the transitionability of the existing system is required to ensure that the desired future system is reached in an optimal way (with maximum benefit and minimum cost both now and in the future).

6.2 Examination of the Approach for Designing for UWDS Transitions

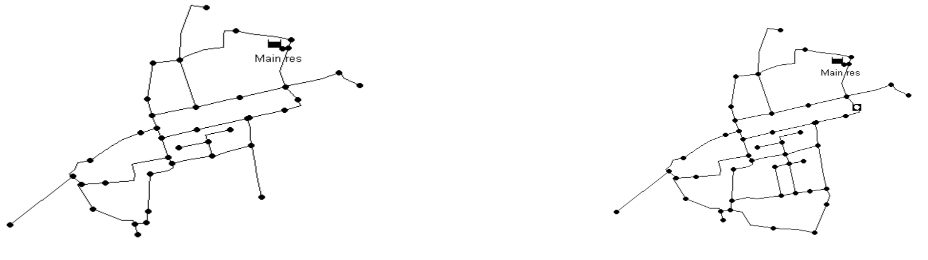
The identification of the appropriate future states of the I-UWDS was developed based on scenarios. Scenario analysis was used because there was limited statistical data and or a probabilistic description of the future events. To simulate realistic future scenarios to match the increased urbanisation and rapid population growth three future transitions scenarios and three possible transition pathways were hypothetically generated based on a study of maps, historical documents, physical observation and studying google maps on how the City has transitioned. During scenario development, rapid population growth and urbanization is assumed to cause an increase in demand beyond the normal growth rates. As a result the future uncertainties for the UWDS are presented by three hypothetical future UWDS transition scenarios shown in Figure 6-3 (b)-(d). A summary of the growth in demand and pipe length through the transition phases is presented in Table 6-1. Details of the characteristics of the existing UWDS and the other scenarios of the I-UWDS$_{1\text{-}3}$ can be found in the Appendix D. Where: the Subscript 1-3 represents the transition Phases 1-3. The characteristics of the transition scenarios for the I-UWDS are summarized in Table 6-1. While the pipe and node characteristics of the transition scenarios can be found in the Appendix D.

Table 6-1: Differences in I-UWDS Transition scenarios

UWDS Figure	Existing Fig 6-2 (a)	I-UWDS$_1$ Fig 6-2 (b)	I-UWDS$_2$ Fig 6-2 (c)	UWDS$_3$ Fig 6-2 (d)
Pipes (No)	28	35	47	60
Nodes (No)	25	30	41	50
Demand (LPS)	6.89	14.10	31.31	69.54
Length (M)	4532	6056	8497	10676

The case study has one water tank with pipes increasing from 28 to 60 with the pipe length increasing from 4500 m to 10,000 m in three transition periods. During the same period the number of demand nodes increase from 25 to 50 while the demand increases from 6.89 to 70 litres per second.

(a) Original TCDZ (b) TCDZ- Transition phase



(c) TCDZ- Transition phase (d) TCDZ- Transition phase

Figure 6-3: Scenarios for the future I-UWDS between three transition periods

The options for transitioning I-UWDS were formulated and these were: (i) Conventional approach-based on existing system (business as usual); (ii) Transition without UWDS transition platform; and (iii) UWDS transition platform based on a new system. The implementation of the case study followed the UTIAM design framework and the PTIC formulations generated in Chapter 6. With the future UWDS scenarios known and plausible UWDS transition pathways identified, testing the case study involved: (i) changing combination of pipes and pipe cohorts retained in an UWDS while analysing the PTIC; and (ii) Establishing the optimal strategy for transitioning the I-UWDS. The permissible means allowed for transitioning the UWDS were the replacement of existing pipes with new pipes of equal or larger diameters. The unit costs for pipe replacement were similar to those from Multiple Industries Uganda the biggest supplier of ISO approved pipes in Uganda which are presented in Table 6-2.

Table 6-2: Unit Costs for pipe laying in 2012 (Multiple Industries 2012)

Sno	*Pipe Dia*	*£/m*
1	40	9.1
2	50	9.3
3	60	9.7
4	70	10
5	80	10.3
6	90	10.7
7	100	11.2
8	110	11.8
9	125	12.1
10	152.4	12.8
11	203.2	17.8
12	254	22.5
13	304.8	29.2
14	355.6	36.2
15	406.4	43.6
16	457.2	51.5
17	508	60.1
18	609	77
19	762	105

6.2.1 GA parameters for the Case Study

The tools for designing for UWDS transitionability developed in Chapter 6 were used to identify the optimal approach for transitioning the UWDS for Iganga. This was done by considering the PTIC for different pipes and pipe cohorts for I-UWDS. First, the preliminary investigation values of crossover probability and mutation probability were selected and investigated further to identify the parameters that were used for further analysis. The results of the GA operator testing process were studied using 10 runs in order to determine the GA stopping criteria, the PTIC for a generation of 20, 50, 100, 150, 200,300 and 500 was plotted for population sizes of 100, 200 and 300. The Figure 6-4 shown indicates that while an increase in the generation improved the convergence of the GA, the PTIC achieved with a generation greater than 100 did not yield significantly better results than those obtained using a population of 350. Hence a generation of 100 was adopted as the stopping criterion.

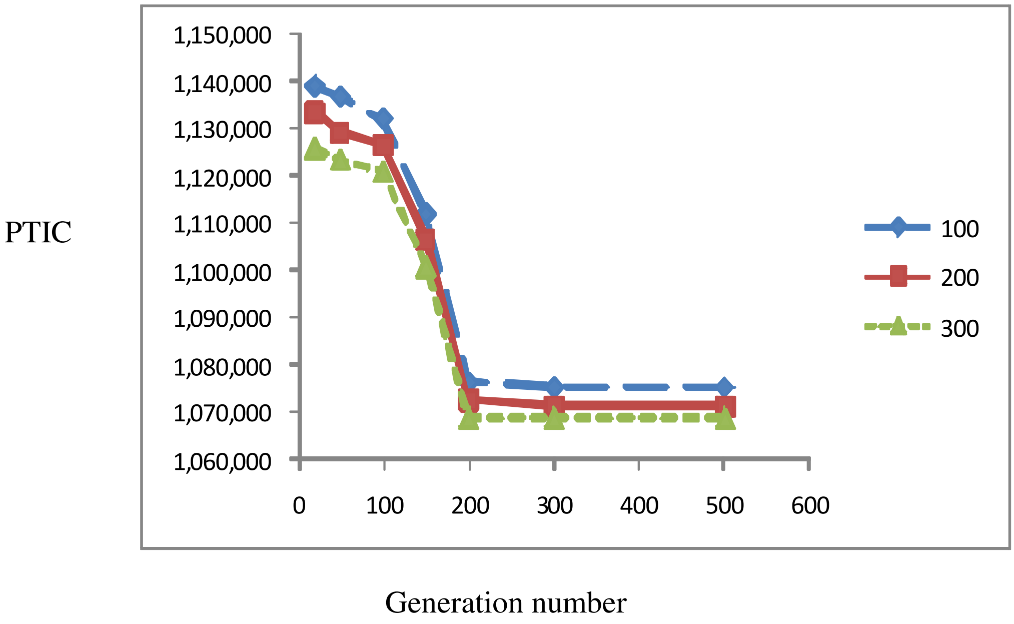


Figure 6-4: Variation of PTIC with generations

Pattern of optimisation of cost in different trials, the five circled places are the locations having higher chances of getting local optimum: the two trials end up around first, one trail around second, one trial around third, three trials around fourth and three trials around the fifth location starting from top to bottom. For each trail run the average PTIC, the maximum and minimum PTIC were calculated and the results are presented in Table 6-3.

Table 6-3: Optimisation output for different trials

Crossover Probability	Mutation Probability	PTIC Max	 Min	 Average
0.7	0.0100	1,501,620	797,149.00	1,074,725.93
	0.0150	1,568,500	892,008.00	1,115,131.96
	0.0200	1,353,420	838,082.00	1,092,459.93
0.8	**0.0100**	**1,471,280**	**741,068.00**	**1,066,813.86**
	0.0150	1,618,200	675,376.00	1,085,055.29
	0.0200	1,379,720	783,197.00	1,067,296.32
0.9	0.0100	1,513,180	876,870.00	1,105,896.11
	0.0150	1,447,890	835,546.00	1,135,104.21
	0.0200	1,366,670	746,757.00	1,103,945.93
1	0.0100	1,644,270	842,579.00	1,086,424.57
	0.0150	1,609,320	875,407.00	1,152,590.39
	0.0200	1,581,760	748,505.00	1,126,172.61

The results show that a crossover probability rate of 0.7-0.8 and a mutation probability rate 0.01-0.02 were the range of operators with the highest effectiveness in establishing the optimal solution of I-UWDS transition problem. The lowest average PTIC of 1,066,814 was obtained with a crossover probability of 0.8 and mutation probability of 0.01.

Although the optimisation process could further be improved by varying the GA operators and parameters, this was not pursued in the I-UWDS case study as it required extended simulations and time. The results of the optimisation using different populations are presented in Figure 6.4

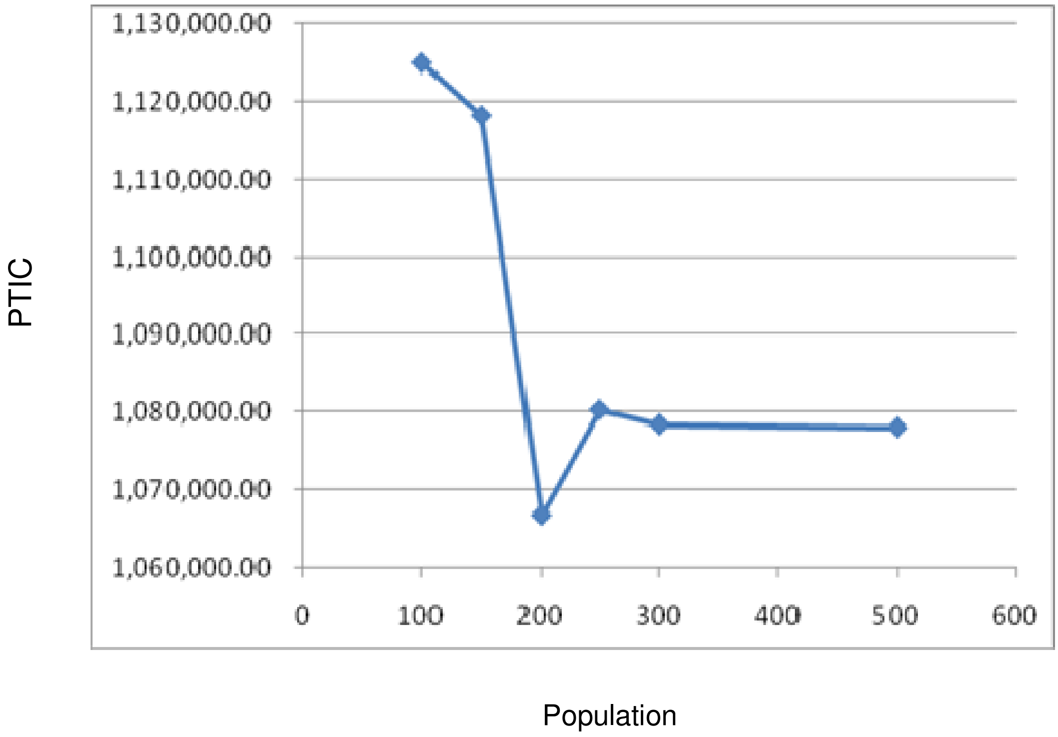


Figure 6-5: Variation of PTIC pattern with populations within a generation

The PTIC for a population of 100, 150, 200, 250, 300 and 500 was ascertained. It was observed that while an increase in the population improved the performance of the GA, the PTIC achieved with a population greater than 200 did not yield significantly better results than those obtained using a population of 200. Hence a population size of 200 was adopted as the optimal population used in the I-UWDS transition problem.

6.2.2 Computation of SII

To compute PTIC of the I-UWDS, computation of the socio-economic impacts of the UWDS is required. The SII were established from the zones in which the pipes and pipe cohorts are located. The demarcation of I-UWDS into transition zones was carried using the spatial analysis tool (Sempewo et al. 2011). The results for the transition zones created for I-UWDS are shown in Figure 6-6.

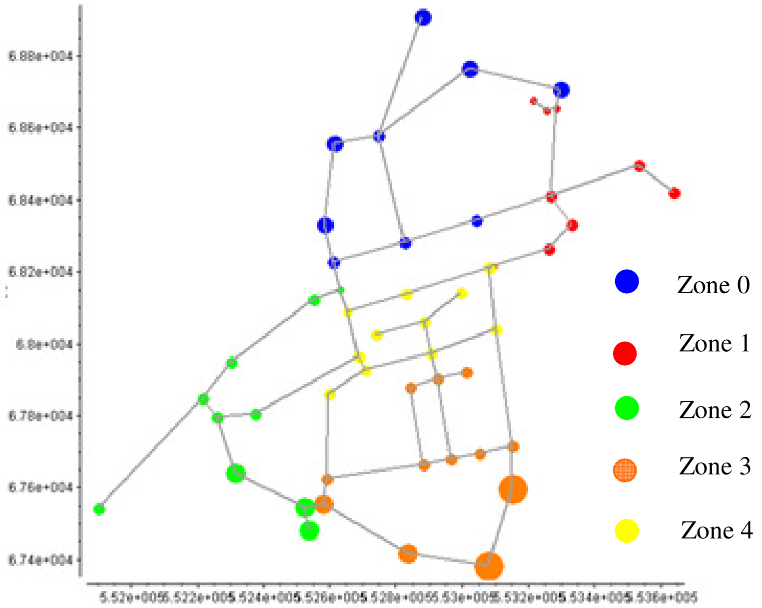


Figure 6-6: SII Zones for I-UWDS obtained using the zoning tool

The SII were computed based on the SII framework developed in Chapter 4. The computations were based on secondary data sources from The UDHS report; and the district and council development plans. The details of the computations are elaborated in Chapter 4 and the results for SII for the different zones are shown in Table 6-4.

Table 6-4: SII for I-UWDS Zones

Zone	Description of zone	SII
0	Zone 1-Bugumba-Nothern Zone	0.97
1	Zone 2-Western-Jinja Rd Zone	1.3
2	Zone 3-Kasokoso I & II	0.7
3	Zone 4-Toror Road-Eastern Zone	1.52
4	Zone 5Nkono I & II	0.81

6.2.3 PTIC for Pipes and Pipe Cohorts for I-UWDS

Figure 6-7 shows the variation of PTIC computed by the GA. As mentioned in Chapter 5, pipes of the I-UWDS when retained or transitioned in an I-UWDS will have varying impacts on the future I-UWDS. In addition to analysing PTIC based on TIC only, socio-economic impacts and impacts due to operation and maintainace such as those due to leakage (LIC) and those due to pipe breaks were considered (BIC). For the Iganga Case Study, the PTIC vary between £ 938,219 and £1,686,935 and the contributions of the LIC and BIC vary from pipe to pipe however they are 5% maximum.

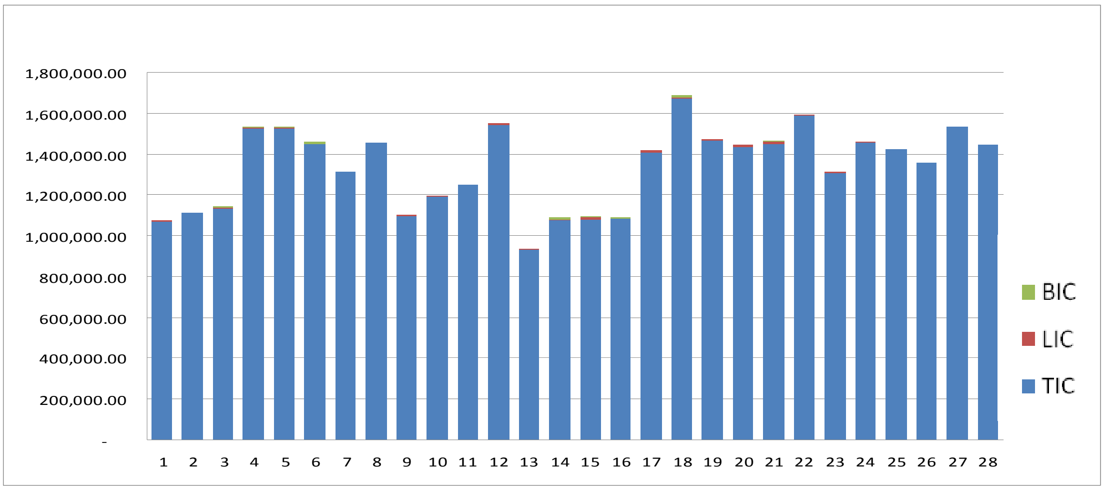


Figure 6-7: Variations of TIC, LIC and BIC for different Pipes of I-UWDS

Figure 6-8 expands the results of Figure 6-7 and presents the % contributions of BIC, LIC and TIC to PTIC for each pipe. For example the PTIC for pipe 15 in Figure 6-7 are contributed by almost 100% of TIC. Figure 6-8 zooms into the results of Figure 6-8. Based on the analysis TIC contribute 95.4% and LIC & BIC contributes 4% and 0.6% respectively A plot of the PTIC for the different scenarios is presented in Figure 6-9 and the contribution of the PTIC for each pipe of I-UWDS during the life of the pipe and pipe cohort is presented in Figure 6-10. The figures show that the PTIC for pipes increase from scenario 1 to scenario 3 and generally the rank of the pipe does not vary significantly.

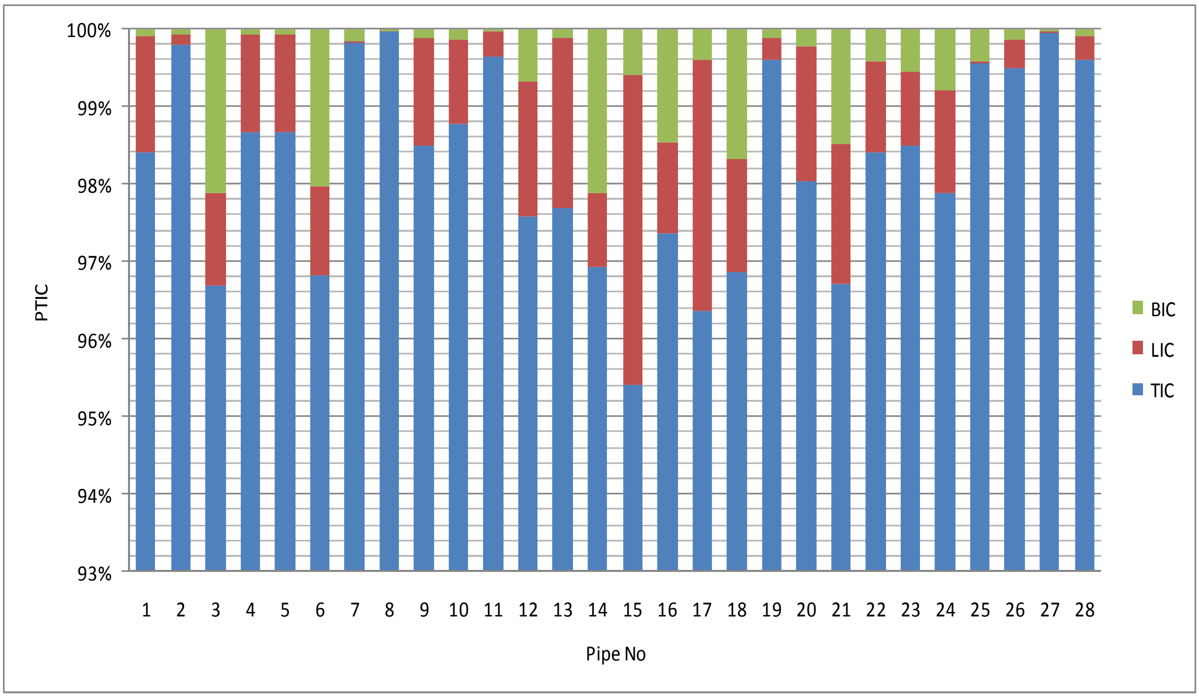


Figure 6-8: Proportions of TIC, LIC and BIC for different Pipes of I-UWDS.

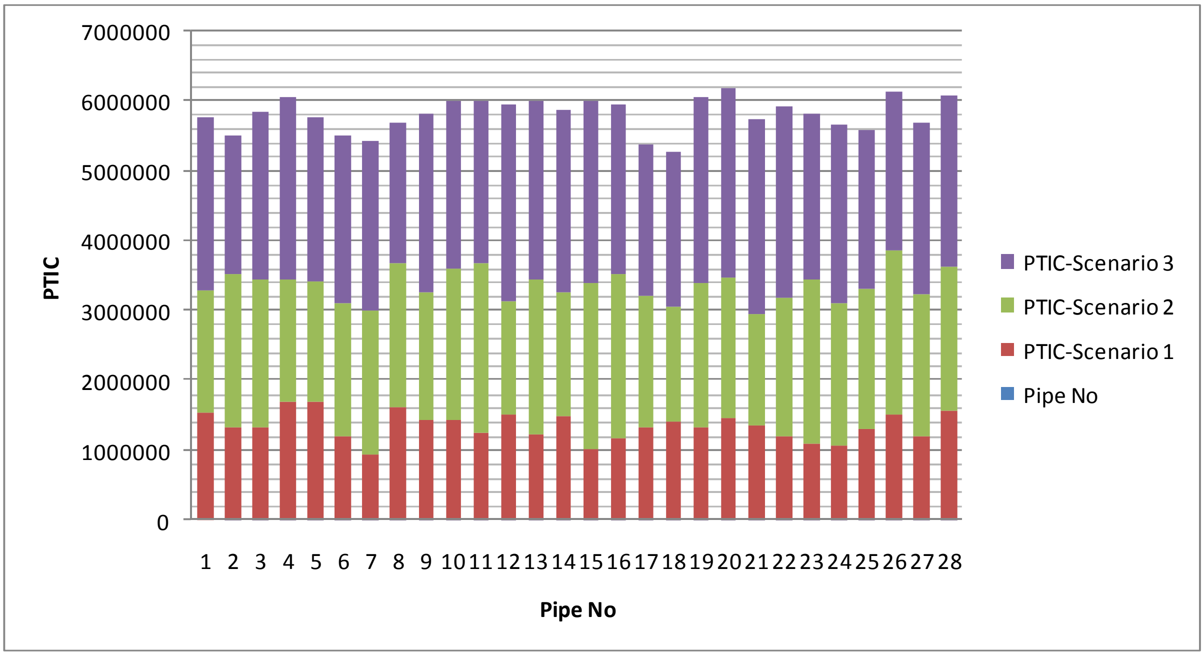


Figure 6-9: Contribution of PTIC for different I-UWDS scenarios

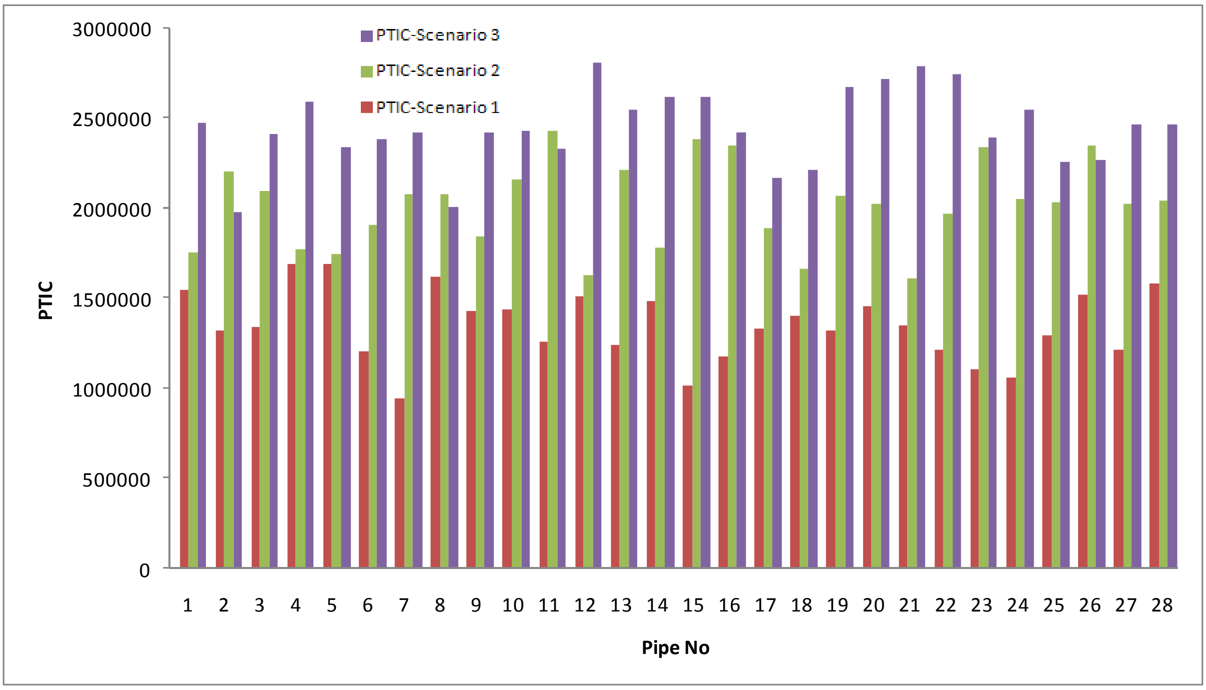


Figure 6-10: PTIC for the different future I-UWDS scenarios.

The impact of the PTIC on the performance of the I-UWDS was also analysed and is presented in Figure 6-11. It was observed that different pipes had varying impacts on the performance and transitionability of the I-UWDS. The performance was derived from a summation of pressure deviations at the nodes while the transitionability was computed from the relationship between the performance of the I-UWDS and the PTIC. The relationship is shown in Equation 6.10. The relationship between PTIC, performance and the NTS varies differently between the I-UWDS pipes presented in Figure 6-11. This means that pipes have different impacts on the future transitionability of UWDS. This attribute that can be used to eliminate pipes with potentially high future transition impact costs.

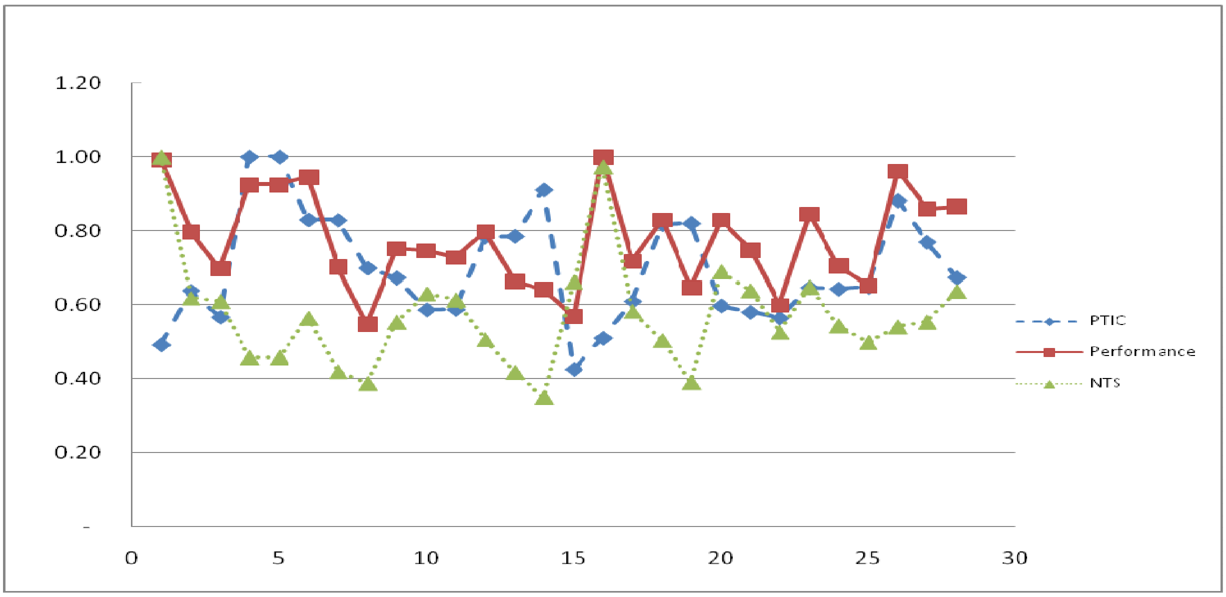


Figure 6-11: Variation of PTIC with Performance and Transition Index

6.2.4 Prioritization of I-UWDS pipes based on pipe criticality [PTIC vs SIC]

A review of prioritization of pipes based on criticality of a pipe for future transitionability based on PTIC and SIC was also undertaken on the I-UWDS. The results of the prioritization are shown in Figure 6-12. The classification of the transition criticality follows the pipe prioritization decision models in technical literature (Engelhardt et al. 2000; Lippai and Wright 2005).

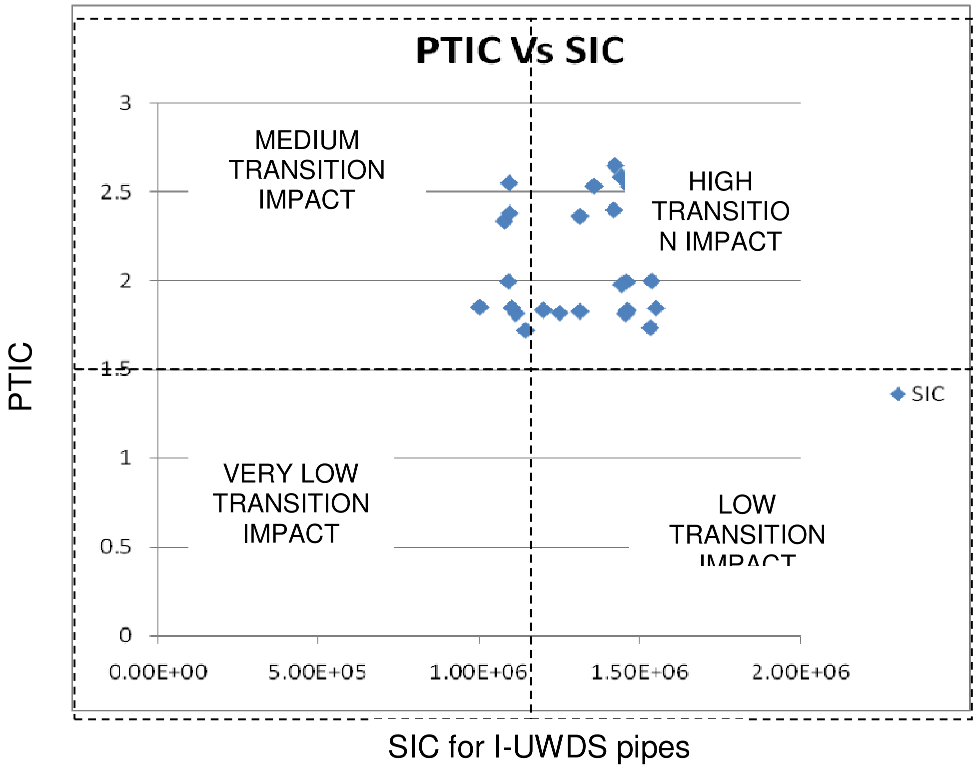


Figure 6-12: Prioritization of I-UWDS pipes based on PTIC and SIC

The graph shows that 63% of the pipes in the existing I-UWDS have a high PTIC and SIC while 27% have a medium transition impact. This means that 2/3 of the pipes have a high transition impact while 1/3 have a medium transition impact. However, the limitation of this approach is that it does not consider the impact of a group of pipes and pipe cohorts. This is due to the fact that there exists legacy infrastructure and urban plans for The I-UWDS area were designed with no consideration of future transitions. The existing I-UWDS originated in the 1960's when populations and urban development were low. Hence given that Iganga has grown from a Town board to a municipality over the past years; means that there is a potential for transitions to have high socio-economic transition impacts.

6.2.5 The I-UWDS Transition Platform

Exploiting the above characteristics of the PTIC approach, the model is used to identify pipes and pipe cohorts of the I-UWDS transition platform that have the least impact on the future UWDS. Due to lack of data for the study area, data from Kampala Water and literature was adopted for the case study: (i) pipe break rate formula

$$PBR_{ij} = 1.52x10^{-3} * \exp(-9.56x10^{-3} Dia_{ij})\tau^{1.899} \qquad [6\text{-}1]$$

derived based on data for the Kampala Water was adopted for I-UWDS and mains breaks of 41/100km/year (Mutikanga 2012); (ii) bursts unit costs for I-UWDS -£1038 /burst; and (iii) the leakage unit cost £2.2 /m^3, based on (Awad et al. 2008).

The impact of different pipes and pipe cohorts on the UWDS transition platform was analysed based on the worst case scenario. For the different I-UWDS transition platforms the PTIC, TIC, LIC and BIC are analysed for each of the proposed future scenarios. A plot of the variation of PTIC, LIC, TIC, BIC for pipes and pipe cohorts of the I-UWDS transition platform for three transition scenarios is presented in Figure 6-13.

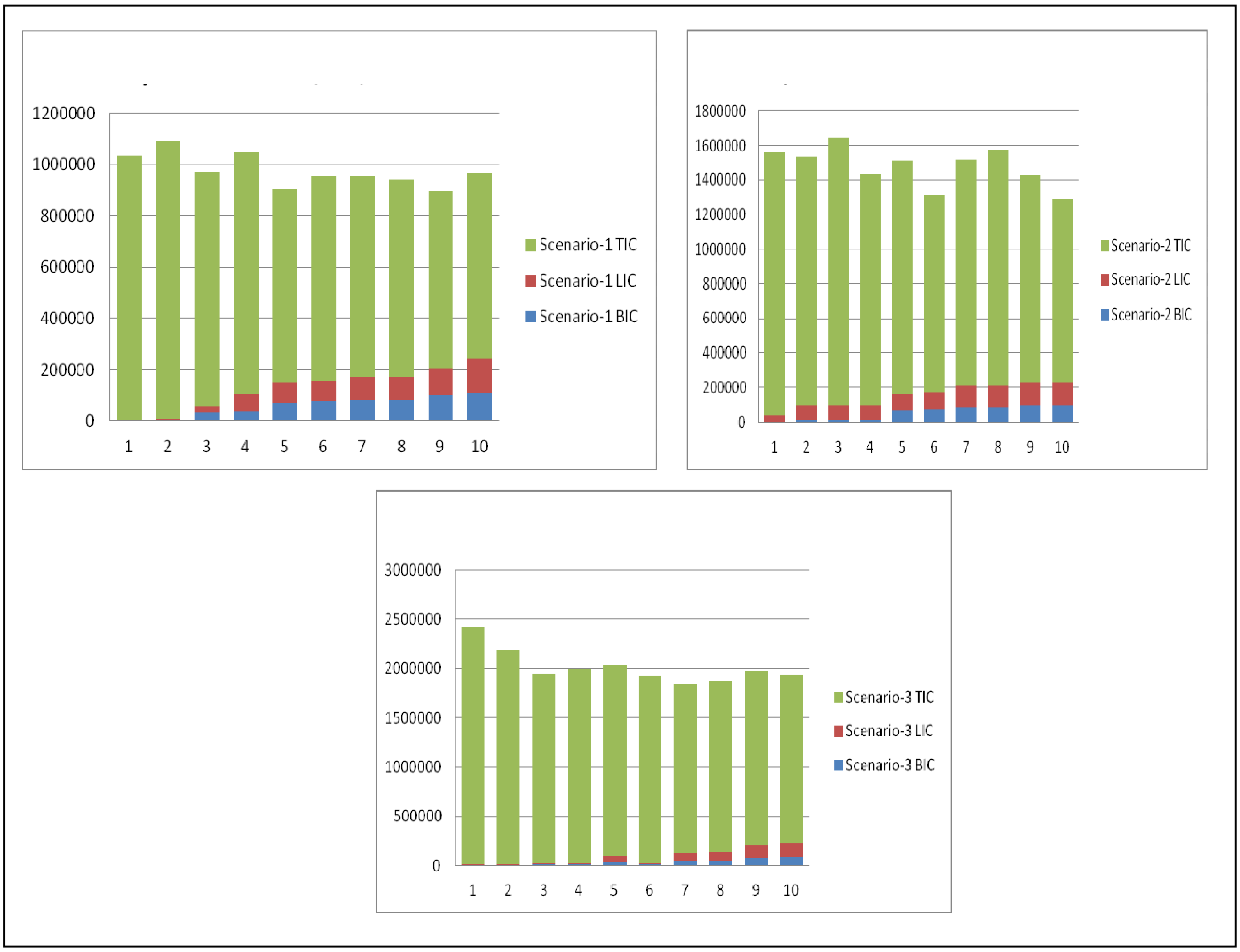


Figure 6-13: Pattern of PTIC, TIC, LIC and BIC with increase in number of I-UWDS transition platform elements.

The results show that the largest proportion of costs for transitioning I-UWDS for all three scenarios is the TIC. TIC is in effect the measure that captures the impact of the technical characteristics of the incumbent UWDS on the future system. This confirms that upgrading UWDS based on the conventional approach that considers only LIC and BIC is not sustainable. Thus makes the existing UWDS susceptible to technical lock-in. This is because conventional approaches rarely consider TIC during the design and upgrade of UWDS. Hence to minimise transition impact and switching costs in the future, largest costs savings can be achieved when the UWDS systems are upgraded with the consideration of TIC.

The variation of the PTIC for the different I-UWDS transition platforms with the network transition score (NTS) is presented in Figure 6-14.

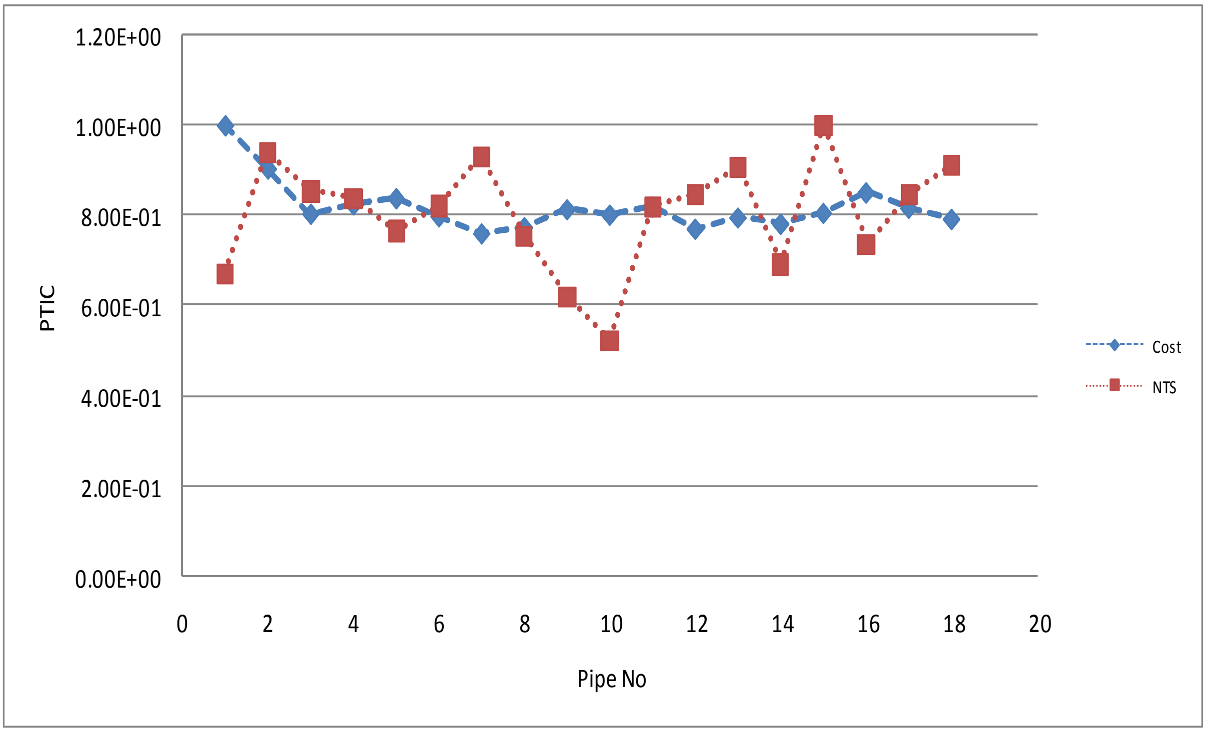


Figure 6-14: Variation of PTIC with NTS for the I-UWDS transition platform

It is observed from Figure 6-14 that PTIC for the different pipes have varying impacts on the cost and performance of the future I-UWDS. Hence pipes and pipe cohorts of the incumbent UWDS can be ranked based on their impact on transition/switching cost (PTIC) and performance (NTS) of the future system. This property can be adopted as criteria to identify pipes and pipe cohorts with the least impact (cost and performance) that constitute I-UWDS transition platform.

For the optimal components of the I-UWDS transition platform, The TIC, LIC and BIC for the different scenarios are analysed. The variation of The TIC, LIC and BIC for the different scenarios is presented in Figure 6-15. It was observed that whereas BIC and LIC generally increased with increase in the number of I-UWDS transition platform elements for each scenario, The TIC decreased.

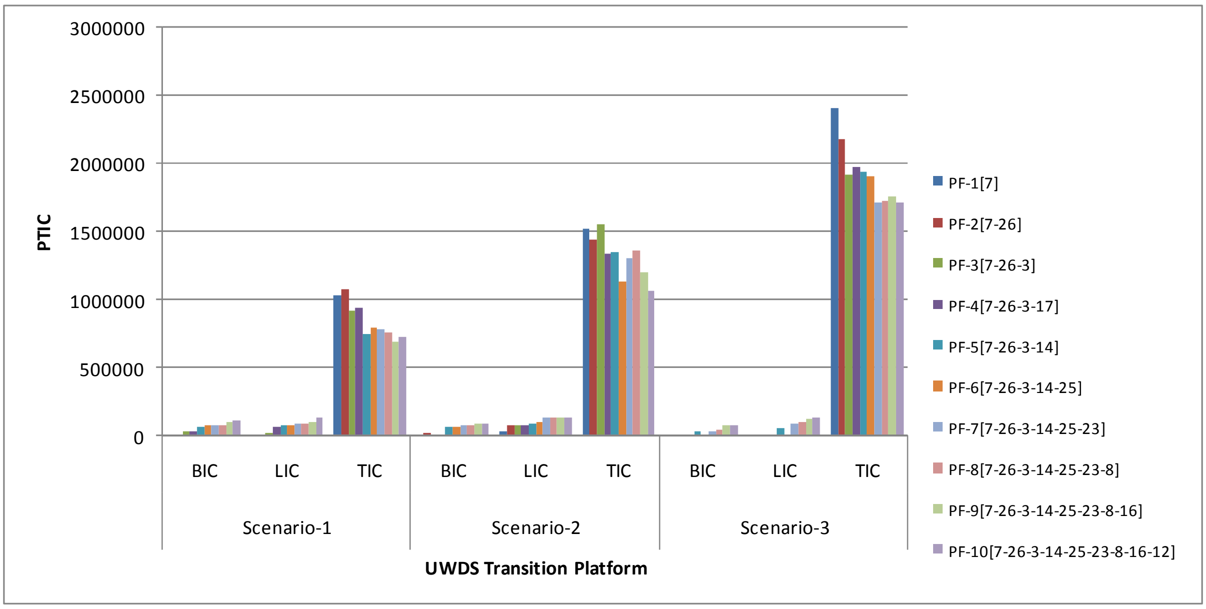


Figure 6-15: Variation of PTIC with NTS for the I-UWDS transition platform in the different scenarios

The maximum PTIC observed for the three scenarios was £ 1,941,970, £1,290, 000 and £967, 000 for scenario 3, scenario 2 and scenario 1 respectively. The general remark is that the approach for the UWDS correctly reduces the costs for transitioning I-UWDS as the number of pipes and pipe cohorts increases until when the GA cannot get feasible results for an extra addition of a pipe or when the costs for transitioning the UWDS rise significantly. As a result, 18 pipes from I-UWDS can be retained in future UWDS with minimum impact on the hydraulic performance and cost of the system. Pipes 7, 26, 3, 17, 14, 25, 23, 8, 16 and 12 are identified as the optimal components of the I-UWDS transition platform. It is important to ensure that the performance of the system is not compromised while aspiring to reduce the costs for transitioning in the future. While PTIC decreases with increase in incumbent pipes retained in the future system, the performance of the system reduces. After this point pipes of the incumbent I-UWDS have to be replaced with the variable pipes of the UWDS transition platform.

6.2.6 Comparative Analysis of the I-UWDS Transition Options

A comparative analysis of the I-UWDS transition options: (i) transition I-UWDS based on the existing system; (ii) transition without I-UWDS transition platform; and (iii) the transition based on the I-UWDS transition platform was implemented on the I-UWDS test case to validate the suitability of the approach. The comparisons were carried out by comparing the lifecycle PTIC which included TIC and OIC. The OIC included BIC and LIC. The proposed approach was used to establish the PTIC for the different options during the comparative analysis. The results of the comparative analysis for the three I-UWDS transition options are presented in Figure 6-16 and Table 6-5 . The results show differences in I-UWDS transition options life cycle costs. The results show that the costs for the option of transitioning I-UWDS based on the I-UWDS transition platform is lower than the option for transitioning without the I-UWDS transition platform.

Table 6-5: Comparison of I-UWDS Transition Lifecycle costs for the Three Approaches

Conventional Approach- Based on an existing system			PTIC	Transition without UWDS Transition Platform			UWDS Transition Platform Based on PTIC		
Phase 1	Phase 2	Phase 3		Phase 1	Phase 2	Phase 3	Phase 1	Phase 2	Phase 3
Not feasible	Not feasible	Not feasible	BIC	184,120	110,685	36,790	109,639	91,565	83,782
			LIC	308,970	160,883	98,064	132,960	131,367	137,651
			TIC	416,307	1,164,050	1,926,490	724,489	1,068,200	1,720,530
PTIC for UWDS transition phase				909,397	1 ,435,618	2,061,344	967,088	1,291,132	1,941,963
PTIC for UWDS transition Option					4,406,359			4,200,184	

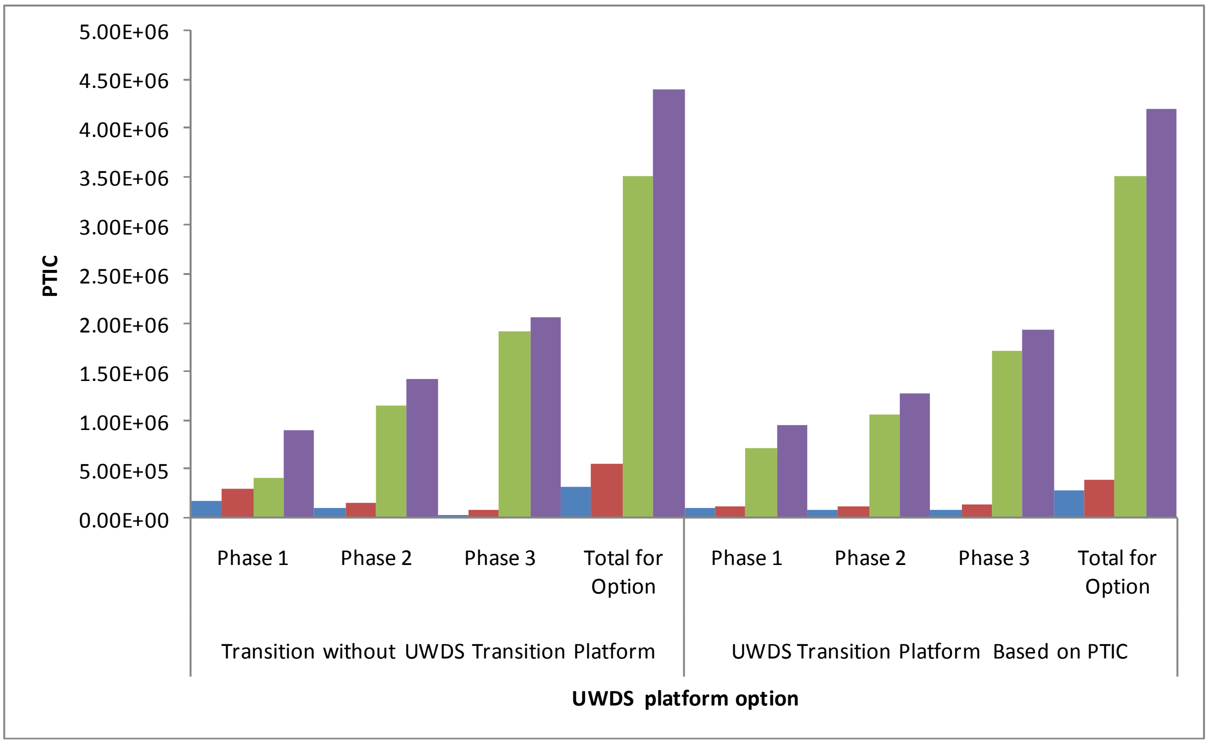


Figure 6-16: PTIC for the two I-UWDS transition options

Comparison of life cycle transition costs for the two strategies demonstrate that the transition of Iganga UWDS should be based on an entirely new system which yields lower transition cost. Figure 6-16 shows the transition impact costs for the two design options: transition without I-UWDS transition platform-£4,406,359 and transition based on UWDS transition platform-£4,200,184.

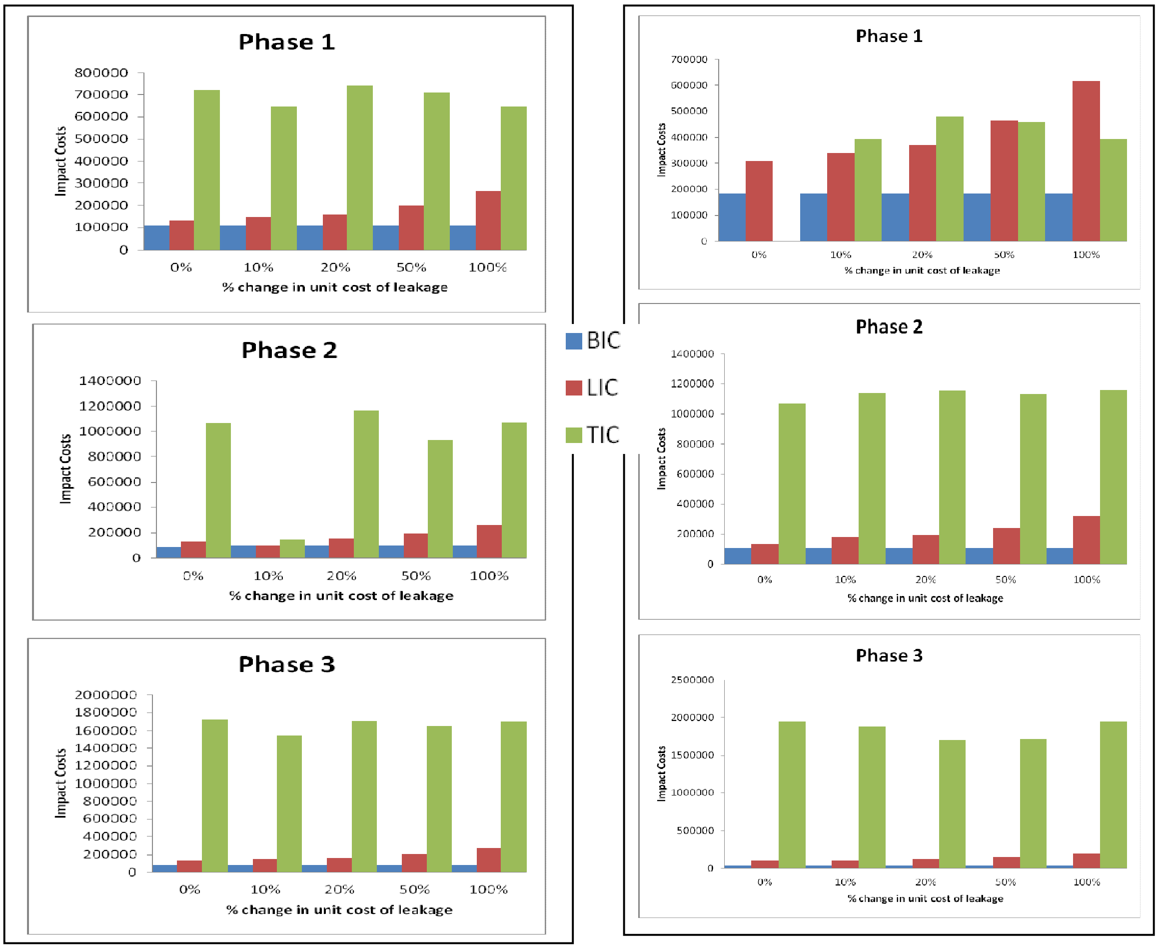
The lower lifecycle costs for the I-UWDS transition platform are attributed to the fact that pipes and pipe cohorts with high PTIC are eliminated during the process for designing the transition of the I-UWDS. This is consistent with literature on product platforms that demonstrates the capability of the concept to reduce cost and performance when developing products within an uncertain environment (Liu et al. 2010). Using the I-UWDS platform enables early elimination of components that are likely to cause relatively large transition costs and impacts. On the other hand, the high transition costs due to the conventional approach could be attributed due to the fact that legacy infrastructure and design principles lock-in the I-UWDS. For example, pipes other than 7, 26, 3, 17, 14, 25, 23, 8, 16 and 12 of the I-UWDS are highly likely to lock-in the I-UWDS. Transitioning the I-UWDS based on an existing system was not feasible due to the failure of the tool to obtain feasible solutions. This may be an indication of the failure of the system due to technological lock in. Hence transitioning an I-UWDS based on the transition platform concept will enable a considerable amount of savings compared to the conventional approach of building on an existing system. For the case of I-UWDS this is estimated as £206,105. The estimate was obtained from the difference in PTIC between the two proposed UWDS transition options.

6.3 Sensitivity Analyses

The main attributes used in the determining the most efficient and effective approach for transitioning I-UWDS are the UWDS transition impact costs i.e., LIC, BIC, TIC and the increase in demand represented by increase in nodal demands and network pipe length. These will depend on the characteristics and type of asset stock. In the case study the location where the network has grown and demand have been assumed to remain constant and the variabilities / sensitivities have been taken care of by creating three scenarios with varying demand and increase in network size. Hence LIC, BIC, TIC are most likely attributes to influence the model output. Sensitivity analysis was therefore carried out for LIC, BIC, and TIC to assess their impact on the proposed model for transitioning UWDS.

6.3.1 Sensitivity of PTIC to Unit Cost of Leakage

The sensitivity of the model was undertaken by varying the unit cost of leakage by, 10%, and 20% , 50% and 100% of the original values of 2.5 £/m3 Awad et al (2008), while maintaining other parameters of the model constant. The process for testing the sensitivity of the model was implemented for the three UWDS transition scenarios (I-UWDS$_1$- I-UWDS$_3$) to analyse the variability across the three I-UWDS transition scenarios. The results of the sensitivity analysis are shown in the Appendix D. Figure 6-18 summarises the results of PTIC with respect to a percentage change in unit cost of leakage for the I-UWDS transition platform and the I-UWDS without one.



(a) I-UWDS Transition Platform b) I-UWDS without UWDS Transition Platform

Figure 6-17: Sensitivity of PTIC to unit cost of leakage

It is observed that PTIC has a medium sensitivity to variations in the unit cost of leakage for all the three transition phases. However, an increase in LIC is observed with an increase in transition phases while BIC remains constant irrespective of the UWDS transition option analysed i.e., transitioning based on the I-UWDS transition platform and the transitioning without considering future transitionability. The increase is attributed to the increase in the percentage of the unit cost of leakage from 0% to 100%. It is important to note that in the first phase for the option of transitioning without considering future transitionability, the proportion of LIC and BIC to PTIC becomes significant when the unit rate of leakage is increased above 50%.

6.3.2 Sensitivity of PTIC to Unit Cost of Burst Repair Costs

The sensitivity of the model was undertaken by varying the unit cost of burst repair costs by 10%, 20%, 50% and 100% of the original values of 1310 £/burst (Awad et al. 2008), while maintaining the model parameters constant. The sensitivity testing process was implemented for the three UWDS transition scenarios (I-UWDS1- I-UWDS2) to analyse the variability across the three I-UWDS transition scenarios. The results of the sensitivity analysis are shown in the Appendix D. Fig 6-19 presents the summary results of the variation of PTIC with the increase in the percentage change of the unit cost for burst repair costs for the two I-UWDS transition options analysed.

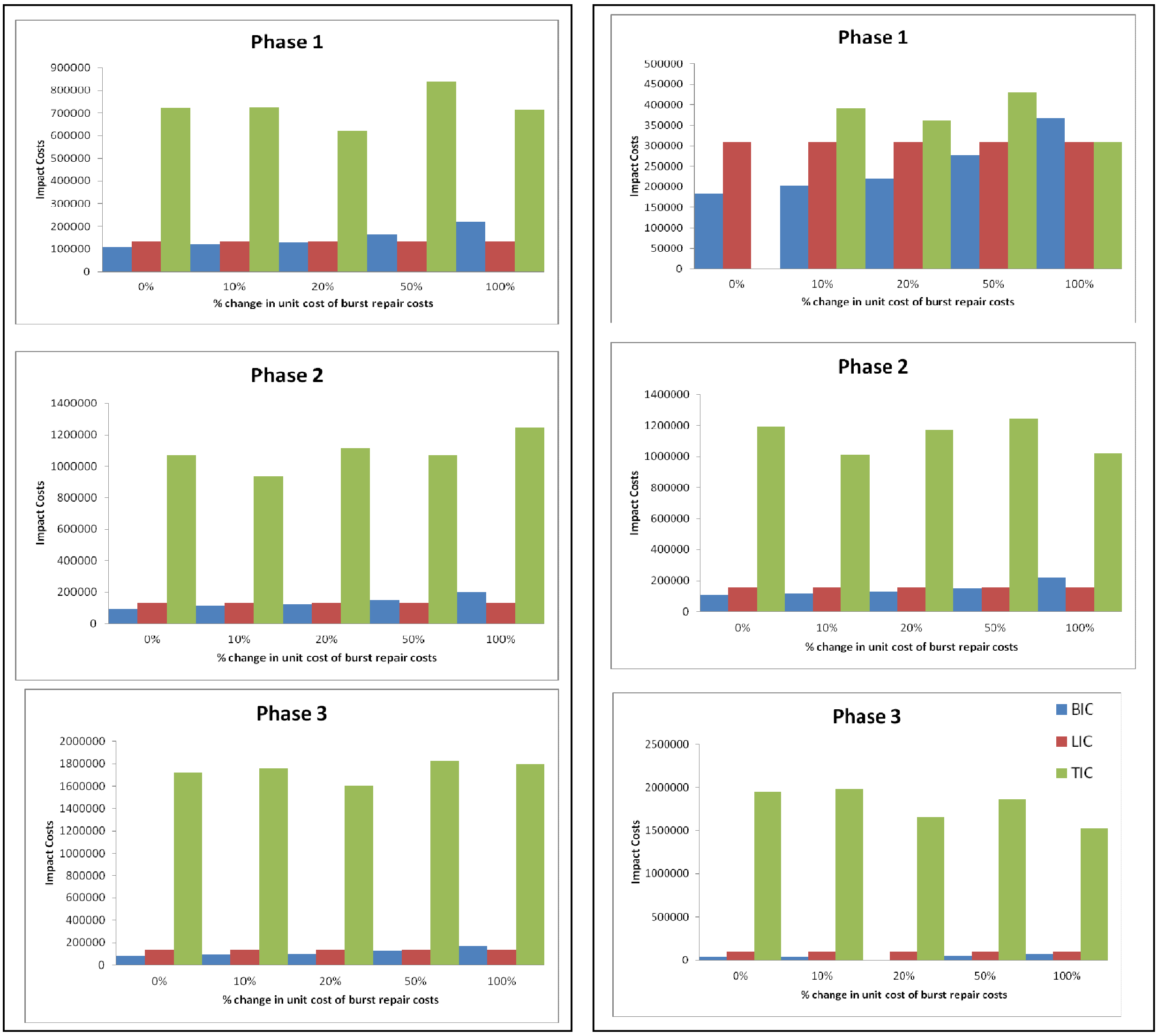


Figure 6-18: Sensitivity of PTIC to unit cost of burst repair costs for I-UWDS Transition Platform

The results show that PTIC has a relatively low sensitivity to the variation in the unit cost of leakage for all the three transition phases and transition options. However, an increase in BIC is observed with an increase in transition phases while LIC remains constant irrespective of the UWDS transition option analysed.

The increase is attributed to the increase in the percentage of the unit cost of burst repair costs from 0% to 100%. It is important to note that when the unit rate of leakage is increased above 50% in the first phase of the transition option; the proportion of LIC is redistributed increasing to a 50%. However, this does not affect PTIC.

6.3.3 Sensitivity of PTIC to the weights of LIC, BIC and TIC

The impact of the weights used for LIC and BIC and TIC in the PTIC optimisation problem was investigated on the I-UWDS Case Study. The sensitivity of the PTIC optimisation was undertaken based on running 10 optimisations using 7 different weight combinations. The selected weight combinations to analyse the sensitivity of the cost for a transition option range between 0.01-1 were applied to the LIC, BIC and TIC. The impact of the weights of the LIC, BIC and TIC was analysed by examining the PTIC generated from the optimisation process.

The weight combinations considered included: [1 1 1], [1 0 0], [0 1 0], [0 0 1], [0.01 0.495 0.495], [0.495 0.01 0.495] and [0.495 0.495 0.01]. The weights of 0 and 0.01 were used to cancel the influence of the weights on the optimisation process. The contribution of LIC, BIC and TIC for the different variable weights was analysed and the results of the sensitivity analysis are shown in Table 6-6

Table 6-6: Results of sensitivity analyses for the TIC, LIC and BIC weights

Serial No	Variation of Weights			PTIC (£)						Life cycle costs		Savings
				UWDS transition platform			Without transition platform			UWDS Platform	No Platform	
	TIC	BIC	LIC	Phase 1	Phase 2	Phase 3	Phase 1	Phase 2	Phase 3			
1	0.33	0.33	0.33	967,088	1,291,132	1,941,963	909,397	1,435,618	2,061,344	4,200,184	4,406,359	Yes-£206175
2	1	-	-	744,658	1,110,010	1,524,460	467,728	1,305,240	1,655,430	3,379,128	3,428,398	Yes-£49270
3	0.01	0.99	-	117,437	101,259	95,736	129,440	98,385	47,499	314,432	275,324	No-£39108
4	0.01	-	0.99	139,589	112,522	112,109	213,793	99,685	90,509	364,220	403,987	Yes-£39767
5	0.01	0.5	0.5	120,096	126,860	112,547	159,624	130,464	78,982	359,503	369,070	Yes-£9567
6	0.5	-	0.5	403,844	630,600	840,118	297,863	629,320	968,896	1,874,562	1,896,079	Yes-£21517
7	0.5	0.5	-	376,423	629,402	840,762	278,396	581,255	960,186	1,846,587	1,819,837	No-£26750
Total per phase				2,869,135	4,001,785	5,467,696	2,456,241	4,279,967	5,862,846	Overall		Yes-260439
Transition option Total				12,338,616			12,599,055					

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Whereas the overall PTIC reduced in value for all weight variations, this did not affect the priority rank for the option for transitioning the UWDS based on the I-UWDS transition platform in five out of seven cases of the weight variations. The prioritization has been based on comparison of the savings realized between the two transition options. There is no cost saving when only BIC is considered (see Row 3). On the other hand there is no cost saving when only BIC is combined with TIC; combined at a ratio of 1:1 (see Row 7). In the rest of the weight combinations and in the overall comparison of the approach for transitioning based on the UWDS transition platform vis a vis that without the transition platform costs savings are realized. Based on the results of the sensitivity analysis of the weights, it can be concluded that irrespective of the weights used, there is generally a maximum cost savings when the UWDS is transitioned based on the UWDS transition platform

CHAPTER SEVEN

CASE STUDY–II: RUBAGA WATER DISTRIBUTION NETWORK

7. Introduction

This chapter presents the application of the theory, the approach and frameworks developed in Chapter 2 to 5 and results from the testing of the sensitivity carried out in Chapter 6 on the Rubaga Water Distribution Network (RWDN), part of Kampala Water, for National Water and Sewerage Corporation (NWSC).

Based on the aforementioned approaches and sensitivity results, the options with the least future UWDS transition impact costs for the case study were identified. The case study was selected because of availability of information on the transition of Kampala water system, unlike Iganga with no infrastructure and weak institution, Kampala represents a typical city in a developing country with mature infrastructure and rigid institutions, and (iii) being one of the branches in NWSC making it possible to adopt data and parameters from other NWSC areas in case of missing data. Due to the limited availability of the case study data parameters, data and assumption from other case studies in technical literature was adopted. This is because it was not possible to generate the required amount of data during the period of study. The study aimed to establish the mode for transitioning RWDN with the least transition impact costs on the future UWDS. Identify the driver’s barriers, opportunities and limitations for transitioning RWDN. Apply the developed theory and model in a discrete zone in the RWDN in Kampala. The case study is implemented based on descriptive/qualitative approach based on Chapter 2 and 3 to establish the drivers and barriers for the transition of RWDN and quantitative approaches based on models developed in Chapter 4 and 5. Based on the case study application, the evidence base for the proposed approach is strengthened. Hence the optimal strategy for transitioning the RWDN is established. The results for the case study application could be beneficial to NWSC when planning for the transition of RWDN in the future.

Kampala Urban Water Distribution System (KUWDS); the largest branch of National Water and Sewerage Corporation is located in Kampala the Capital City. Kampla Cityis the largest commercial centre in Uganda. Kampala City is composed of five divisions: Lubaga, Central, Makindye, Nakawa and Kawempe. Only a specific study area within Kampala was selected for application of the model. Therefore, the proposed transitioning approach is applied to Rubaga water distribution network (RWDN), a hydraulically isolated network (shown below) that covers the greater Rubaga Division. Rubaga Division is located between Latitude: 0.3029 and Longitude: 32.5529 (Figure 7-1).

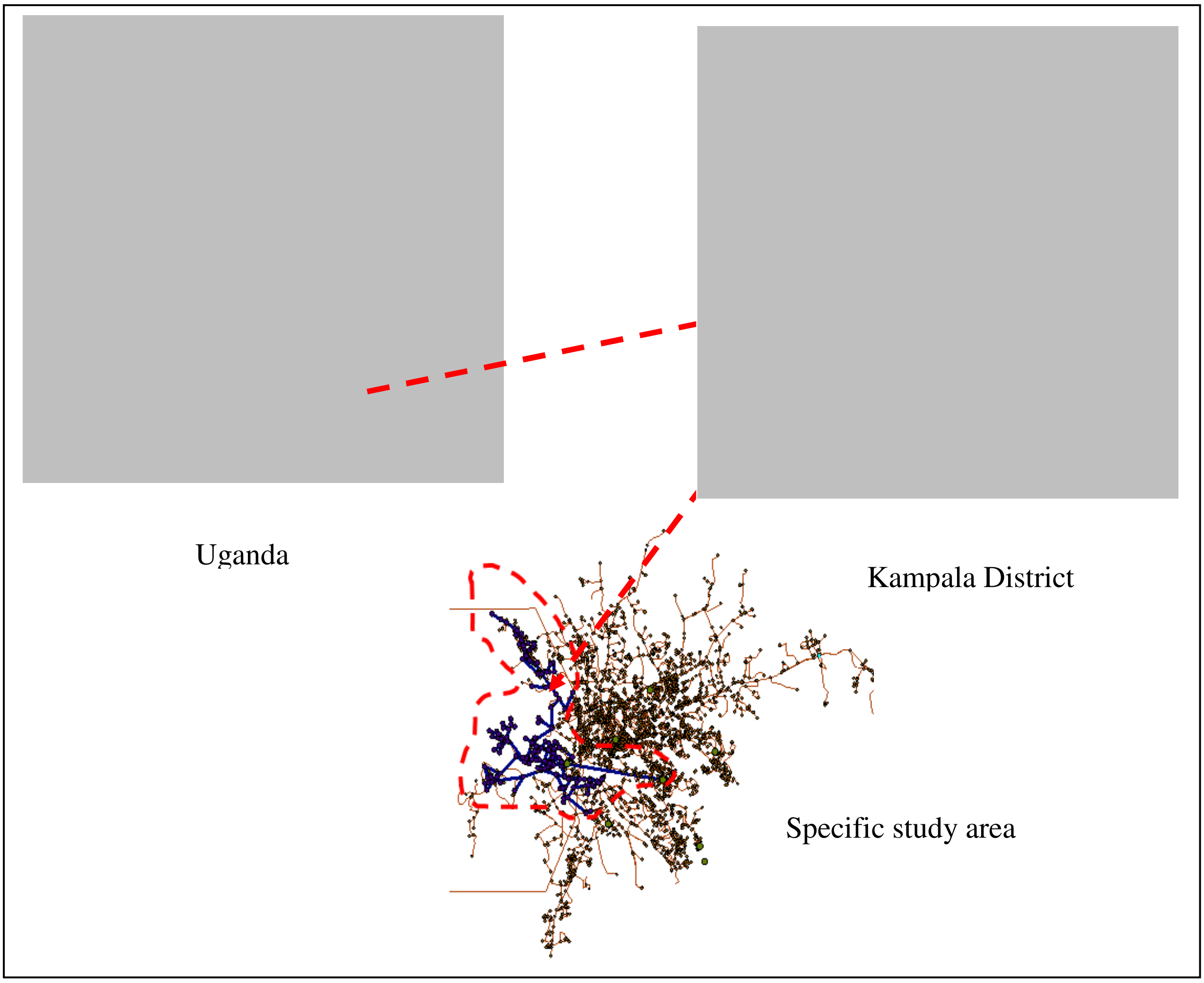


Figure 7-1: Location of Kampala Water and Specific Study Area

This chapter is structured in six sections. Section 7.1 introduces and gives a brief overview of testing the proof of concept on Rubaga in Kampala Water. Section 7.2 describes the Kampala Urban Water Distribution System study area. Section 7.3 describes the design for transitionability for Rubaga Water Distribution Network (RWDN). The analysis of the transition potential of RWDN based on pipe criticality and the transition platform approach are presented in section 7.4. Section 7.5 compares and evaluates the most feasible transition options for RWDN. Finally, Section 7.6 presents the sensitivity analyses of input parameters

7.1 The study Area- Kampala Urban Water Distribution System

Kampala Water serves Kampala City Council Authority, the largest and administrative capital of Uganda. The city lies in the central part of Uganda at the coordinates of 00 19N, 32 35E. Population estimates based on 2002 National Census Data estimates that 2.5 million inhabitants live within the service area of which 1.21 million live in Kampala District (UBOS 2002). With an annual growth rate of 3.8%, Kampala is one of the fastest growing cities in the world. The area is managed administratively as 10 branches, however hydraulically, it is managed as five zones supplied by five primary storage tanks located in Muyenga, Naguru, Rubaga, Mutungo and Gunhill and a couple of secondary storage tanks. The service area encompasses an area of about 300 km^2 and the water network that is supplied by the water tank of Rubaga is what is used in the case study. The case study area is a typical city in a developing country with a mature conventional UWDS with rigid institutions that operate in silos and is under pressures to transition. The pressure is due to high population growth rates, urbanisation and mature infrastructure. Kampala City has grown tremendously from a population of 2850 to the present day population. Population increase in Kampala metropolitan area is responsible for increased water demand. As such, the evolution of the UWDS in Kampala has developed to meet the increased demand. The growth of Kampala has been characterized by the sprawl into hitherto rural areas engulfing formerly satellite towns within a radius of 32 kilometres. The urbanized area has become metropolitan, spanning approximately 386 square kilometres. However, the growth and expansion is associated with lack of infrastructure, social services posing severe planning and environment problems. To meet the increase in population and urbanisation, the original KUWDS constructed in 1930 to provide water to the colonial masters has evolved into the existing UWDS (Figure 7-2).

Figure 7-2: Transition of Kampala UWDS [1927-2006] (Nilsson 2006)

The original UWDS for Kampala was constructed in the 1930s to provide water to the colonial masters (Nilsson 2006) and has transitioned into the current system (Figure 7-2). The drivers that have influenced the transition include: (i) the formation of the UWDS transition structures that commenced with the development of the National Water Policy developed by the Government of Uganda in 1999; and (ii) global change pressures such as rapid urbanization and population growth that had outstripped UWDS of their capacity to meet the levels of service of UWDS. The recent population increase in Kampala is responsible for increased water demand.

To deal with this challenge, NWSC has invested in existing UWDS infrastructure to counter these changes. For example NWSC has recently increased the water production from 39 million to 52 million cubic meters and the water main length of the utility at a rate of 104 km/ year for the last five years in the period 2004-2010 (NWSC 2010) as shown in Figure 7-3.

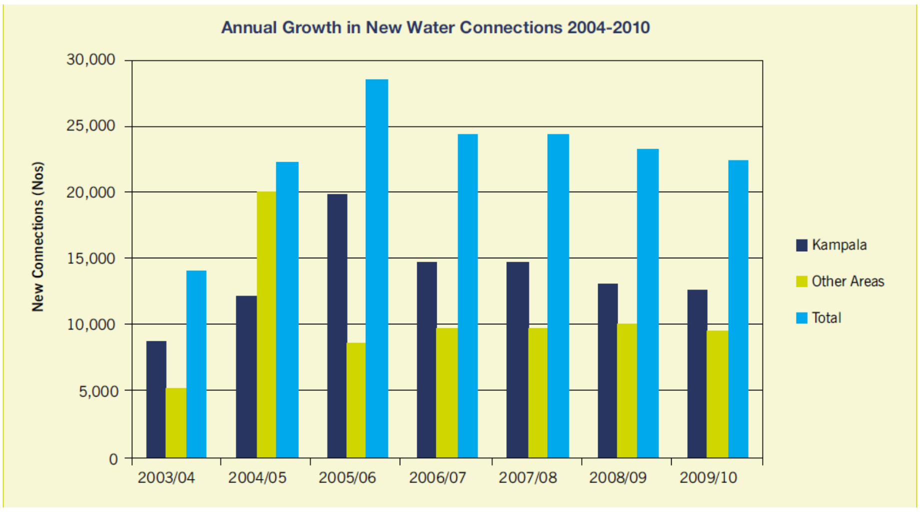


Figure 7-3: Annual Growth in New Water Connection for the NWSC Area (NWSC 2010)

However, these investments face a limitation of legacy infrastructure that causes high UWDS transition costs. Moreover, these investments have been outpaced by the rapid population growth and urbanisation, resulting in water shortages and low pressures in most parts of distribution system. Whereas the statistics show an increase in coverage, this growth in terms of extensions and service coverage also mean impact on the level of service of the existing UWDS. The intervention has been based on a reactive approach which is not optimal or may lock us in. Moreover the KUWDS transitions have focussed on increasing the capacity of the Gaba Water Treatment Plant from a production capacity of 2000 m3/day to a 144,000 m3/d (NWSC 2010), which is less than the required demand of 200,000 m3/day and the predicted demand of 342, 000 m^3/d in 2025.

KUWDS has been selected as a case study because it is characterised by a history of transitioning over the past two decades. Notable among this transition is the service coverage that has increased from 48 % in 1998 to 72 % in 2007. The water network coverage has increased by 45%, ~850 km of water main extensions whereas the new connections have increased from 3,317 No to 22,218 No per year. As a result, total connections have increased from 50,826 to 125,000. The details of these improvements are shown in (Figure 7-4). However, the rate of increase in pipe connections and network length is less than the transitions in the UWDS, which impacts the performance of the UWDS, and hence the need to transition the UWDS.

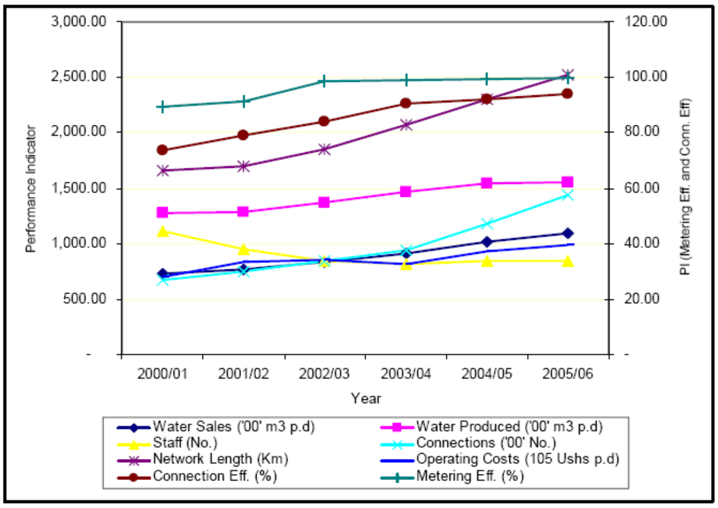


Figure 7-4: NWSC Partial Performance Trends (Mugisha 2007)

Despite the recent growth of the city, Kampala Water is still stuck with most parts of the UWDS infrastructure and management practice inherited from the colonial period where municipal water services were developed in urban centres. After Uganda's independence in 1962, management of these UWDS was handed to indigenous institutions with inadequate human/institutional capacity and financial constraints which limited the capacity of utilities to expand their coverage and to cope with the rapid urban growth (due to rural urban migration). This period was preceded by the period between 1972 and 1988 where the city was devastated by prolonged conflict. Institutions and infrastructures emerged out of this period with deep scars. A backlog in infrastructure service delivery accrued, while the UWDS were rapidly deteriorating. Kampala City grew in a haphazard manner, where infrastructure developments (including urban water infrastructure) occurred on ad hoc basis with lack of proper planning and documentation. Institutions concerned with the different components of the urban water sector operated in silos models without coordination and integration. During this regime, limited progress was made towards the transition from the water supply city to the sewered city.

7.1.1 The Specific Case Study Area

Whereas the case study is Kampala Water, located in Kampala, only a specific study area within Kampala was selected for application of the model. The discrete RWDN was considered because it was possible to hydraulically isolate it from the entire network without affecting the hydraulic characteristics of the greater Kampala network. To generate the discrete case study network, a moderate level of skeletonization was applied to the original consultants design to create a hydraulically discrete water supply subsystem upon which the model was applied.

The RWDN is one of the original zones of the UWDS network designed by Eng Morris in 1930 (Nilsson 2006). Originally the network was designed to serve: the original headquarters of the Buganda Kingdom in Mengo, including Lubiri Palace, The Buganda Parliament and The Buganda Court of Justice; the headquarters of the Colonial Masters in Old Kampala; Rubaga Cathedral; Namirembe Cathedral; and the areas of Namirembe, Mengo, Mulago and Makerere. The water network that supplies the area expanded in response to the rapid urbanisation and population growth. As a result, the RWDN has transitioned to cover the areas of Nansana on Hoima Road; Kyengera and Busega on the road to Kampala- Kigali highway; and Bulenga on Mityana road; among others. The network consists of a pipe network of 100km, serving a total population of 344,752 people and a total area of 33.8 Sq.km. The RWDN is supplied by gravity from a single tank located on Rubaga Hill and has the following characteristics:

(i) One tank that supplies the area by gravity

(ii) 100km pipe work with sizes ranging between 50-450mm Diameter

(iii) Supply zone elevation of between 1157-1224m

(iv) A booster station further downstream of the network

(v) 14,900 water connections, most of which are household connections

(vi) UWDS average pressure of 67.26m.

Few efforts have been made to transition the system in tandem with these change pressures. Despite the great improvement on the RWDN, urbanisation and population growth have outpaced the evolution rate of the existing UWDS. In addition, the transitions of the RWDN have been driven reactive trial and error approach leading to a complex bandaged spaghetti network that is locked in, thus unsustainable.

Water supply has not kept pace with population growth and has resulted in water shortages and low pressures in most parts of distribution system. According to the NWSC progress report (NWSC 2010), Rubaga is one of the areas in Kampala Water that continues to complain of intermittent water supply and dry zones. To this extent, RWDN requires transitions that eliminate today’s challenges without limiting transitions in the future. Under such circumstances, the assessment of the transitionability of the existing system is required to ensure that the desired future systems are reached in an optimal way (with maximum benefit and minimum cost both now and in the future).

7.2 Design for the Transitionability of RWDN

The RWDN was used to verify the proposed approach to designing for UWDS transitionability. The description of the network is provided in Section 7.5. The case study follows the UWDS transition impact assessment method (UTIAM) developed in Chapter 6. The UTIAM approach involves: (a) development of options for transitioning the RWDN; (b) development of scenarios for future RWDN; (c) quantification of the transition impacts of the pipes and pipe cohorts for RWDN; and (d) Evaluation -Comparison and selection of the transition option for RWDN. The quantification of transition impacts due to retaining pipes and pipe cohorts in an UWDS in the third section is based on the assumption that pipes within an UWDS impact the transitionability of the UWDS in the future in different ways. Based on implementation of the UTIAM design approach the optimal strategy for transitioning the RWDN is recommended. Details of the process implemented in the case study are elaborated.

7.2.1 Development of Option for Transitioning the RWDN

The options for transitioning RWDN were formulated based on the pathways developed in Chapter 3 and these were: (i) Conventional approach-based on existing system (business as usual); (ii) Transition without UWDS transition platform; and (iii) UWDS transition platform based on a new system. This option was developed using the two stage optimisation approach developed in Chapter 6.

7.2.2 Future Scenarios for Future RWDN

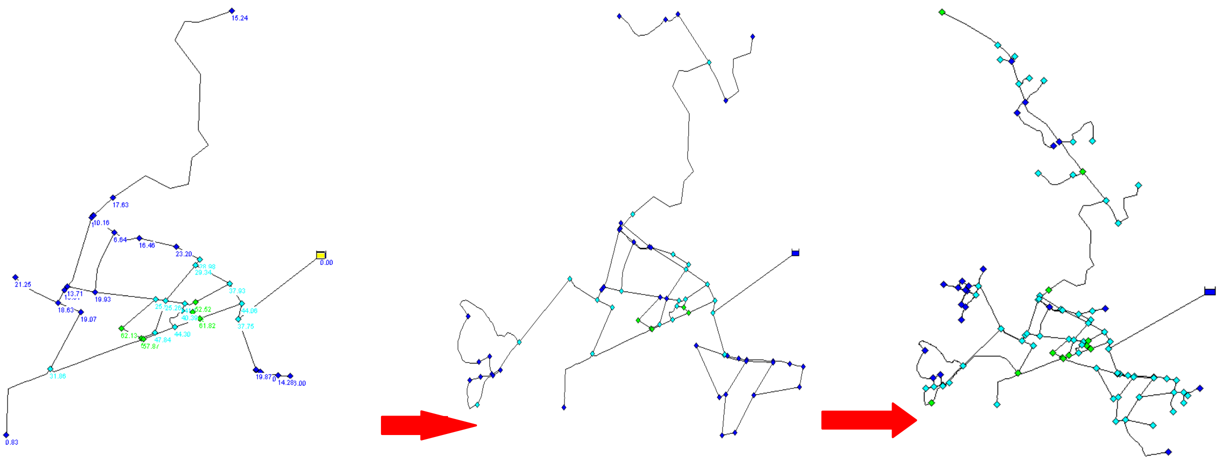
The development of the future RWDN based on scenario analysis which is a process widely used to generate future states based on analysis of alternative worlds (Hsia et al. 1994; Wang and Watson 2010). The scenario analysis approach was found to be a suitable approach because RWDN lacked reliable historical statistical data or even data that could be used to generate a probabilistic description of the future UWDS. Based on these scenarios future states for transitioning RWDS were generated.

As a result three future transitions scenarios and three possible transition pathways were hypothetically generated based on a study of maps, historical documents, physical observation and studying goggle maps on how the City has transitioned. During scenario development, rapid population growth and urbanization is assumed to cause an increase in demand beyond the normal growth rates. As a result the future uncertainties for the UWDS are presented by two hypothetical future UWDS transition scenarios (Figure 7-5 (b)-(c)). A summary of the growth in demand and pipe length through the transition phases is presented in Table 7-1. Details of the characteristics of the existing UWDS and the other scenarios of the I-UWDS1-3 can be found in the Appendix 8. Where; the Subscript 1-2 represents the transition Phases 1-2. The characteristics of the transition scenarios for the I-UWDS are summarized in Figure 7-5 while the pipe and node characteristics of the transition scenarios can be found in the Appendix 8.

Table 7-1: Summary of RWDN Transition scenarios

UWDS	Existing Fig 7-2 (a)	$UWDS_1$ Fig 7-2 (b)	$UWDS_2$ Fig 7-2 (c)
Pipes (No)	48	84	125
Nodes (No)	39	68	103
Demand (LPS)	14.26	27	85
Length (M)	28,656	57,402	83,470

The hypothetical case study has one water tank located on Rubaga hill with pipes increasing from 48 to 125 with the pipe length increasing from 28km to 83km in two transition periods. During the same period the number of demand nodes increase from 39 to 100 while the demand increases from 14 to 85 litres per second.



(a) Original network (b) RWDN-Transition phase 1 (c)RWDN-Transition phase 2

Figure 7-5: Scenarios for the future RWDN

Based on these scenarios the developed options for transitioning the RWDN were analysed.

7.2.3 Quantification of PTIC for the developed RWDN Transition Options

Transition Impact Costs (TIC) between the hypothetical RWDN transition scenarios was analysed using a tool that links Visual C++ and EPANET2 software to perform hydraulic simulations of the UWDS during the transition process. The permissible means allowed for transitioning the UWDS were the replacement of existing pipes with new pipes of equal or larger diameters. The unit costs for pipe replacement were similar to those used for the Iganga case study derived from pipe prices obtained from Multiple Industries; the biggest supplier of ISO approved pipes in Uganda (Multiple Industries 2012). PTIC were estimated from a total of SIC, TIC, LIC and BIC represented by Equation 7-1.

$$PTIC = \frac{(1+\alpha)}{(1+r)^{tp}} * \left[W_{OIC} \sum_{P \in \beta} (LIC + BIC)_j^{\;P} + W_{TIC} \sum_{T=\sigma} C^T L^T D^T \right] \qquad [7\text{-}1]$$

TIC was computed from the cost for re-optimising the UWDS when a pipe or pipe cohort is retained in the UWDS. During the re-optimisation process the cost permitted was the price at 2012 for replacing existing pipes with new pipes of equal or larger diameters.

LIC was estimated from the costs of leakage due to pipes and pipe cohorts of the RWDN transition platform [Equation 7-2].

$$LIC = LC * tp * KL_{ij} \times Dia_{ij}^{d} \times e^{a\tau} \left(P_{ij}^{bv}\right)^{LE} \qquad [7\text{-}2]$$

BIC was estimated from the cost of repairing bursts caused by pipes and pipe cohorts retained in the RWDS. The computation of pipe breaks for RWDN was estimated from pipe break prediction model developed following Constantine and Darroch (1996) given by $y = a\tau^{b}$ where y is the pipe break in (No/km /year) , $\tau =$ pipe age in years and a and b are coefficients.

With the information for the main breaks for the RWDN not being available, the rate of pipe bursts for Kampala was assumed to be the rate of pipe bursts for RWDN. The mains break in Kampala is estimated at 41/100km/year (Mutikanga. 2012). Given that the age of the different pipes is known, coefficients a and b were determined from empirical data using regression, Microsoft Excel 2007 Analysis tools and Solver to estimate the relationship between the pipe break rate for RWDN. Details of the pipe data regressed can be found in Appendix 8. The failure rate for the pipes in RWDN can be estimated from:

$$PBR_{ij} = 1.52x10^{-3} * \exp(-9.56x10^{-3} Dia_{ij})\tau^{1.899} \qquad [7\text{-}3]$$

$$BIC = PBRij * Lij * SIC * CB * tp \qquad [7\text{-}4]$$

Where Dia_{ij}= diameter of pipe ij and τ = pipe age in years

Burst impact cost arising from repairing bursts due to pipes and pipe cohorts retained in the RWDS were estimated based on Equation 7-1. The burst unit cost for RWDN was assumed to be £1038 /burst based on (Awad et al. 2008).

The difference in pipe size and age of the RWDN, the costs of leakage arising from the leakage pipes and pipe cohorts retained in the RWDS were estimated based on modified equation by Vela et al (1991) shown in Equation 6-11. The Leakage unit cost was estimated to be £2.2 /m^3, based on the unit cost a customer pays per m3 of water used (Awad et al. 2008). Due to lack of zone specific data, the leakage level RWDN was assumed to be that for Kampala Water. The pipe, a coefficient, was K related to nature of the water network was assumed to be 0.00000564 (Mujuni 2010). During the transition analysis period, hydraulic carrying capacity (C-Factors) for the existing RWDN network were assumed to follow the model in Equation 7-5 presented by (Sharp and Walski 1998)

$$C(t) = 18 - 37.2\log\left(\frac{e + a_1(t + g_t)}{Dia_{ij}}\right) \qquad [7\text{-}5]$$

Where: e = initial roughness in pipe i at the time of installation when it was new (m)

t = time elapsed from present time to future periods (years)

a_1= roughness growth rate in pipe i (m/yr)

g_t = age of pipe i at the present time(time of analysis) (years)

Dia_{ij} = diameter of pipe i (m)

The initial roughness of the pipes in the original network; was retrieved by the model from the existing RWDN network. a_1 is a case based coefficient that depends on pipe material. This typically ranges between 0.066mm/yr and 0.63mm/yr (Walski et al. 1998; Colebrook and White (1973)). In this model a_1= has been assumed to be 0.1mm/yr. The estimate for SIC was based on $SIC_j = \alpha_j = PSI_{s\tan ardised} * SII_{s\tan dardised}$. The PSI was estimated based on (Arulraj and Rao 1995) and SII was computed from the approach development of SII developed in Chapter 3.

Computation of SII

SII was carried out in two stages: (i) Demarcation of the RWDN zones into smaller zones; and (ii) computation of the composite weights SII for the identified zones. The assumption is that pipes inherit the SII of the zones in which they are located.

Demarcation of the RWDN into smaller zones, was undertaken using the spatial analysis tool (Sempewo et al. 2008). The zones were based on the hypothesis that not all pipes of RWDN have the same socio-economic impact on the transition of the system. Based on these zones, pipe impact at zone level were able to be analysed. The Spatial analysis tool has been applied to a few case studies (Sempewo 2008) and has proved as a useful tool to partition highly complex “spaghetti networks”. Whereas the tool produces good results, it is criticized for not having been tested on a real case (Sempewo et al. 2008). Nonethe less the approach was applied to zone the RWDN and the results are shown in Figure 7-6

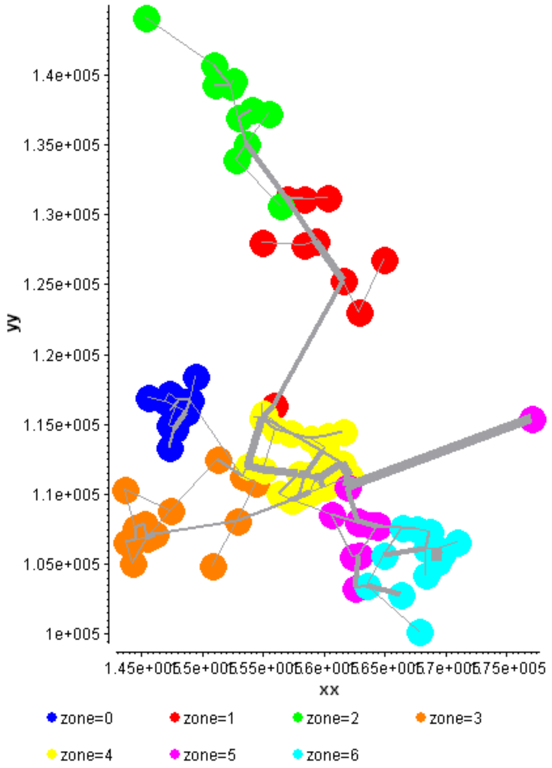


Figure 7-6: SII Zones for RWDN obtained using the zoning tool

Zone zones for RWDN were created for the purposes of developing a SII. Computation of the SII for the created zones was based on the SII framework developed in Chapter 4. The SII were obtained by aggregation of sub-indicators of the Urban Characteristic Impact (UC), Urban Infrastructure Impact (UI) and Socio-economic Impact (SE) indicators. The weights for the criteria and sub-indicators were obtained using the AHP technique. The quantitative data to score the criteria was gathered from secondary sources i.e. UDHS report, the district and council development plans, and from discussions from key experts such as the District Water Officer, the area manager of NWSC, the principal engineer, the water loss control manager and former general manager of Kampala Water, the Principal engineer water loss control and Water network, manager decision support systems and GIS and planner NWSC

The score for the SII criteria and sub -criteria were based on the characterization presented in Chapter 3. SII for the created zones are shown in Table 7-2. Details of the application of the framework can be found in Chapter 3.

Table 7-2: SII for RWDN Zones

Zone	Description of zone	SII
0	Zone 1-Mityana Road	0.39
1	Zone 2-Kasubi,Lungujja, Lubya, Nakulabye	0.64
2	Zone 3-Nansana , Wakiso	0.57
3	Zone 4-Busega, Mutundwe, Kyengera	0.76
4	Zone 5-, Namirembe,Rubaga	0.91
5	Zone 6-Ndeeba Natete	0.85
6	Zone 7-Najanankumbi I I & II-Kabowa	0.68

SII for the developed zones for RWDN is higher than in the least developed areas. Because Zone 1 on Mityana Road is less developed, it has a SII of 0.39. In addition, it has the greatest opportunity to transition because it has fewer barriers that inhibit the transition process.

7.3 Analysis of the Transition Potential of the RWDN

Two approaches for determining the pipes of the RWDN that have the least impact on the future transitionability of the system are sought. These are: (i) the prioritization approach that estimates the criticality of a pipe for future transitionability based on PTIC and SIC; and (ii) the two stage optimisation approach that follows the RWDN transition platform. In both cases, the analysis focused on PTIC derived from the cost of replacing pipes as a surrogate of the impact of the pipes on future transitionability of the UWDS.

7.3.1 Prioritization based on Pipe Criticality [PTIC vs SIC]

The analysis of the RWDN transition potential based on the prioritization approach was determined from a plot of PTIC vs SIC. This enabled the identification of a group of pipes and pipe cohorts with the least impact on the transitionability of RWDN. Details of the results are shown in Figure 7-7.

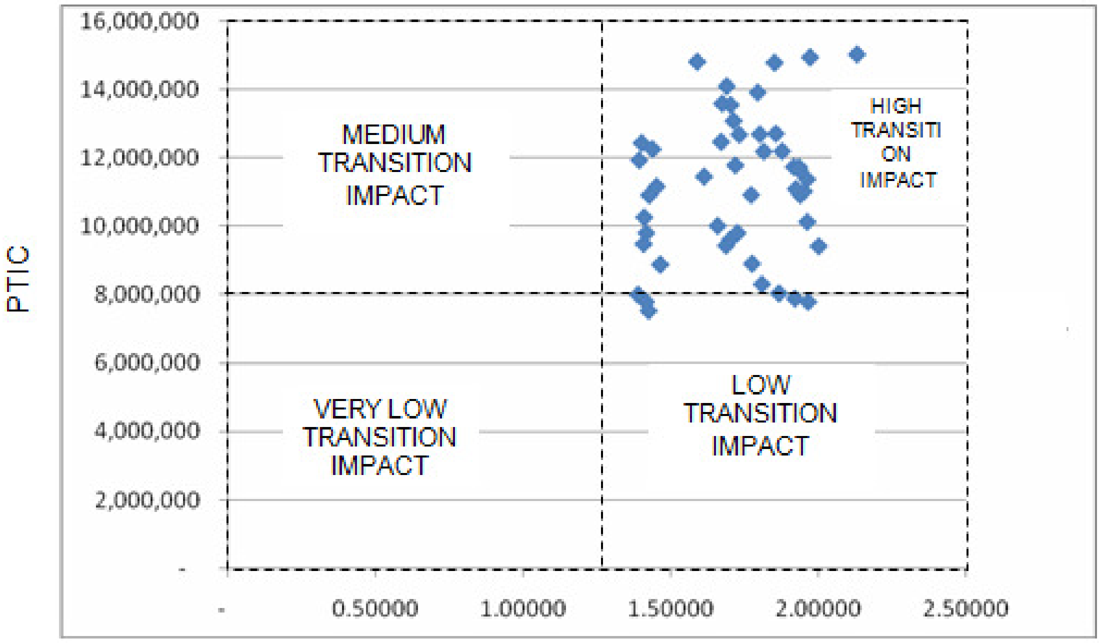


Figure 7-7: Prioritisation of RWDN based on PTIC and SIC

Based on the prioritisation methodology, the pipes and pipe cohorts for RWDN can be classified. 15% of the pipes in the existing RWDN have a low transition impact while 85% have high transition impact. A higher percentage of the existing pipes have a high transition impact because the legacy infrastructure in Rubaga and RWDN were designed with limited consideration of future transitions. Because the original network was designed when populations and urban development were low and that the Rubaga area has grown tremendously over the past years, transitions will have high socio-economic transition impacts.

This means that the greatest volume of transitions will take place in the emerging satellite towns of Kampala such as Zone 1-Mityana Road, Zone 3-Nansana, where the impacts on the socio economic transitions and the infrastructure and urban planning are still relatively low. Although the approach is criticized for being more suited for pipe than for pipe cohorts (does not take care of PTIC for more than one pipe), it is a suitable approach for ranking UWDS pipes for transitioning based on their criticality.

7.3.2 Optimal RWDN Transition Platform

Multi-objective optimisation was carried out for each of the pipes and pipe cohorts using GA’s. PTIC was computed as a surrogate for the costs of redesigning UWDS to meet the changed demand. In addition to the TIC, objectives of OIC that include LIC and BIC were added to optimisation problem. This multi-objective transition problem was reformulated into a single objective using the formulation in Equation 7-1.

Weights for the different objectives were assumed equal. A sensitivity analysis on the case study of Iganga has demonstrated that PTIC is not sensitive to weights. Because of the large optimisation process, the design of UWDS transitionability based on the UWDS transition platform was undertaken using a two stage approach. The approach was: (i) identification of pipes of the incumbent RWDN that have the least impact on the future system; and (ii) identification of the optimal pipe sizes of the transitionable pipes and pipe cohorts of the UWDS (Wei et al. 2009). Both stages were implemented using genetic algorithms (GAs) and were based on the hypothesis that the ranking of pipes based on impact on the future system can be used to identify the optimal pipes and pipe cohorts of the RWDN transition platform on which future additional UWDS components can be transitioned with least impact to the UWDS.

As mentioned in Chapter 6, pipes have varying impacts on an RWDN when retained or transitioned in a RWDN. From the analysis RWDN Pipe 23 has the least impact on the transitioning of the incumbent RWDN to the future while only 15 pipes from the original network for Rubaga can be retained in both scenarios of the future UWDS; the future system without affecting the hydraulic performance and cost of the system. Pipe 23 has the least impact on the transitioning of the incumbent UWDS to the future while Pipes 23, 1, 25, 20, 18, 26, 15 and 34 are identified as the optimal components of the RWDN transition platform. This result is consistent with the results for the approach for prioritisation of UWDS. The location and SIC for the pipes of the platform are presented Table 7-3 .

Table 7-3: Location of pipes in the RWDN Transition Platform

Pipe Index	Description	SIC
6	Zone 7-Najanankumbi I I & II-Kabowa	1.72
7	Zone 7-Najanankumbi I I & II-Kabowa	1.73
8	Zone 7-Najanankumbi I I & II-Kabowa	1.70
9	Zone 1-Mityana Road	1.40
12	Zone 6-Ndeeba Natete	1.88
14	Zone 6-Ndeeba Natete	1.85
18	Zone 7-Najanankumbi I I & II-Kabowa	1.71
19	Zone 3-Nansana , Wakiso	1.58
23	Zone 1-Mityana Road	1.40
26	Zone 5-, Namirembe,Rubaga	1.95
28	Zone 1-Mityana Road	1.40
32	Zone 4-Busega, Mutundwe, Kyengera	1.86
33	Zone 5-, Namirembe,Rubaga	1.93
37	Zone 1-Mityana Road	1.42
38	Zone 4-Busega, Mutundwe, Kyengera	1.80
43	Zone 1-Mityana Road	1.41

According to Unruh (2000) lock-in occurs when the benefits of transitioning are less than the cost of transitioning. In this case study, it is assumed that lock-in of the UWDS occurs when the impact on future cost and performance falls below the set threshold. Hence pipes other than 6,7,8,9,12,14,18,23,26,28,32,33,37,38,43 are retained in the future; and are likely to lock in the RWDN in the future. These need urgent transitioning.

The approach for the UWDS transition approach solution demonstrates that reuse of components of the UWDS based on the platform transitions can enable reduce on the transition effort and cost for future UWDS transitions.

7.4 Evaluation and Comparison of the RWDN Transition Option

As stated in Chapter 6, the objective of analysing and comparing the three RWDN transition options was to identify the most feasible RWDN transition option with the least effort and transition cost. This was implemented by computing the transition lifecycle costs for the three options:

(i) The evaluation and comparison of the RWDN based on the existing system;

(ii) Transition without RWDN transition platform; and (iii) the transition based on the RWDN transition platform. The comparisons were carried out by comparing the lifecycle PTIC which included TIC and OIC. The OIC included BIC and LIC.

Two transition scenarios $UWDS_{1-2}$ were used to assess the merits and demerits of the proposed transition options. The characteristics of the studied hypothetical UWDS, scenarios and are shown in Appendix E. The detailed results of the analysis and comparison between the two transition options are presented in Figure 7-8. The results show that transitioning based on the UWDS transition platform leads to a cost saving of 10% of the future UWDS transition costs.

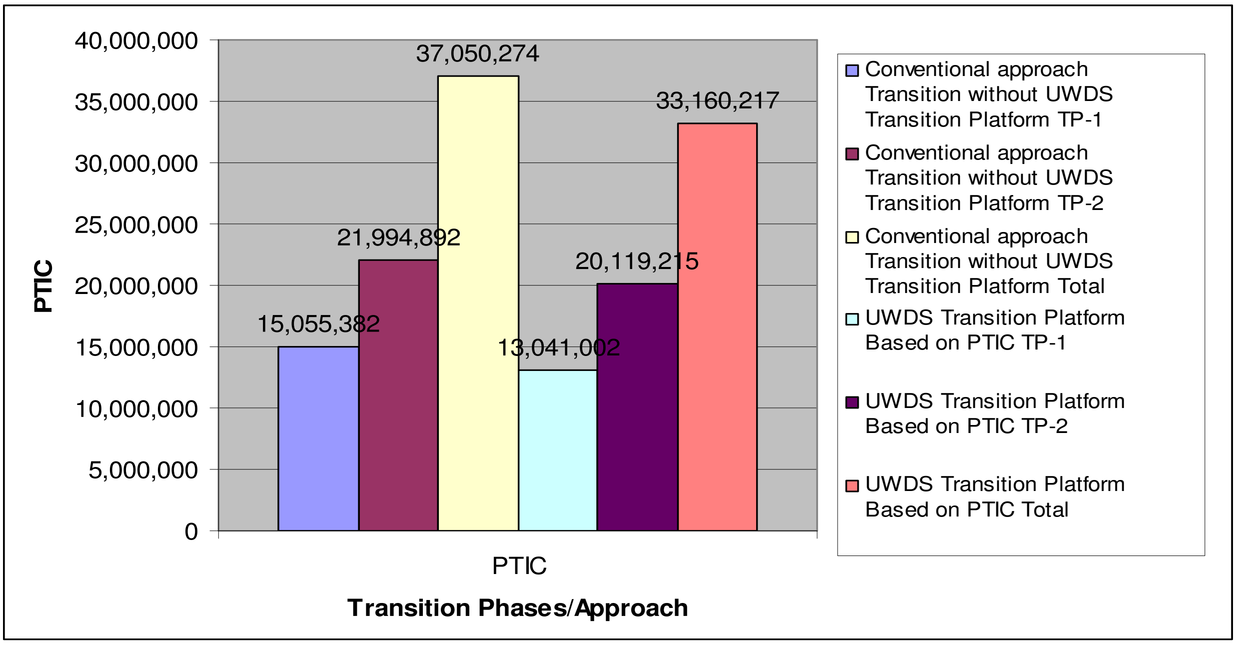


Figure 7-8: PTIC for the two RWDN transition options

Figure 7-8 shows the transition impact costs for the design options: based on existing system-not feasible; conventional approach and RWDN transition platform based on PTIC. The transition lifecycle costs for the options show that costs to transition the RWDN based on the transition platform are lower than the costs to transition the RWDN based on the conventional approach. The lower lifecycle costs for the RWDN transition platform are attributed to the fact that pipes and pipe cohorts with high PTIC are eliminated during process for designing the transition of the RWDN. This is consistent with literature on product platforms that demonstrates the capability of the concept to reduce cost and performance when developing products within an uncertain environment (Liu et al. 2010). Using the RWDN platform enables early elimination of components that are likely to cause relatively large transition costs and impacts. On the other hand, the high transition costs triggered by the conventional approach could be attributed to the fact that legacy infrastructure and design principles lock-in the RWDN. For example, pipes other than 6,7,8,9,12,14,18,23,26,28,32,33,37,38,43 of the RWDN have a high potential for locking in the RWDN. Transitioning the RWDN based on an existing system was not feasible due to the failure of the optimiser to obtain feasible solutions due to technological lock in. Hence transitioning an RWDN based on the transition platform concept minimises future RWDN transition costs

7.5 Sensitivity Analyses of Input Parameters

The sensitivity of the model was tested on the Iganga case study and the model produced good results for the changes in the input parameters for each of the UWDS transition scenarios and options considered. A relatively low sensitivity to the variations in the unit cost of leakage, unit cost of burst repair costs and the weights for LIC, BIC and TIC was observed for the Iganga case study. The sensitivity of the model input parameters for the Kampala case study is also analysed to confirm the results of the Iganga case. Hence sensitivity analysis on the UWDS for Rubaga, Kampala was therefore carried out for LIC, BIC, and weights to increase the evidence base of the sensitivity of the model and to assess their impact on the proposed model for transitioning UWDS.

7.5.1 Sensitivity to Unit Cost of Leakage

With respect to unit cost of leakage, the leakage was increased by, 10%, 20% 50% and 100% while maintaining other parameters of the model constant. The variation of PTIC with increase in unit cost of leakage was observed as shown in Table 7-4 for both the transition phases; two transition phases and transition options i.e. transitioning based on the I-UWDS transition platform and the transitioning without considering future transitionability. The transition impact costs have a very low sensitivity to an increase in percentage of unit cost of leakage. This is because when the unit rate is varied, new optimal solutions for the Kampala Case Study are established. However, for the Kampala Case Study, an increase in LIC is observed while BIC remained constant. The increase is attributed to the increase in the percentage of the unit cost of leakage from 0% to 100%. Based on output results, there is insignificant variation of PTIC with increase in unit cost of burst repair cost. Furthermore, it was observed from the sensitivity analysis that the UWDS transition platform option provided the maximum cost with respect to transitioning the UWDS in most of the optimisations implemented with increasing the unit rate of leakage.

Table 7-4: Sensitivity of PTIC to unit cost of leakage

Transition Phase	% increase	UWDS Transition platform option			Conventional Transition Option		
		BIC	LIC	TIC	BIC	LIC	TIC
Phase-1	0%	1.47E+03	1.02E+03	1.83E+06	5.50E+02	2.03E+03	1.97E+06
	10%	1.47E+03	1.12E+03	1.84E+06	5.50E+02	2.24E+03	1.91E+06
	20%	1.47E+03	1.23E+03	1.97E+06	5.50E+02	2.44E+03	1.98E+06
	50%	1.47E+03	1.53E+03	2.00E+06	5.50E+02	3.05E+03	2.02E+06
	100%	1.47E+03	2.04E+03	1.66E+06	5.50E+02	4.07E+03	1.83E+06
Phase-2	0%	1.66E+03	1.31E+03	1.94E+07	3.90E+02	2.38E+03	2.10E+07
	10%	1.64E+03	1.44E+03	2.02E+07	3.85E+02	2.55E+03	2.16E+07
	20%	1.82E+03	1.60E+03	2.29E+07	3.75E+02	2.68E+03	2.32E+07
	50%	1.56E+03	1.72E+03	2.01E+07	3.90E+02	2.86E+03	2.20E+07
	100%	1.82E+03	2.67E+03	2.09E+07	3.84E+02	4.60E+03	2.12E+07

7.5.2 Sensitivity to Unit Cost of burst Repair Cost

Likewise the sensitivity of the model to the unit cost of leakage was implemented by varying the unit cost of burst repair costs by 10%, 20%, 50% and 100% of the original values of 1310 £/burst (Awad et al. 2008). The increase in percentages was implemented while with model input parameters constant. The results of the analysis are presented in Table 7-2. Less significant variation of PTIC with the unit cost of burst repair cost was observed for both the transition phases and transition options. However, an increase in BIC is observed while LIC remained constant. The increase is attributed to the increase in the percentage of the unit cost of burst repair costs from 0% to 100%. Based on the analysis results PTIC has a relatively low sensitivity to increase in unit cost of burst repair cost. Furthermore, it was also observed that the UWDS transition platform option provided the least future transition impact and maximum cost savings in the majority of the optimisations implemented with increasing the unit rate of burst repair costs.

Table 7-5: Sensitivity of PTIC to unit cost of burst repair costs

Transition Phase	% increase	UWDS Transition platform option			Conventional Transition Option		
		BIC	LIC	TIC	BIC	LIC	TIC
Phase-1	0%	1.47E+02	1.02E+03	1.83E+06	5.50E+02	2.03E+03	1.97E+06
	10%	1.62E+02	1.02E+03	1.70E+06	6.05E+02	2.03E+03	1.89E+06
	20%	1.77E+02	1.02E+03	1.90E+06	6.53E+02	2.00E+03	1.90E+06
	50%	2.21E+02	1.02E+03	1.75E+06	8.25E+02	2.03E+03	1.77E+06
	100%	2.94E+02	1.02E+03	1.91E+06	1.10E+03	2.03E+03	2.42E+06
Phase-2	0%	1.66E+02	1.31E+03	1.94E+07	3.90E+02	2.38E+03	2.10E+07
	10%	1.87E+02	1.32E+03	2.36E+07	4.29E+02	2.38E+03	2.42E+07
	20%	2.18E+02	1.33E+03	2.37E+07	4.68E+02	2.38E+03	2.43E+07
	50%	2.67E+02	1.32E+03	2.37E+07	5.85E+02	2.38E+03	2.43E+07
	100%	3.64E+02	1.33E+03	2.15E+07	7.80E+02	2.38E+03	2.22E+07

7.5.3 Sensitivity to weights of LIC, BIC, and TIC

The impact of the weights used for LIC and BIC and TIC in the PTIC optimisation problem was investigated on the Rubaga; Kampala Case Study. The impact of the weights of the attributes (LIC and BIC and TIC) of the objective function was undertaken by 48 optimisation runs using 7 different weight combinations that is to say: [1 1 1], [1 0 0], [0 1 0], [0 0 1], [0.01 0.495 0.495], [0.495 0.01 0.495] and [0.495 0.495 0.01] applied to the LIC, BIC and TIC respectively. The impact of the weights was analysed by examining the PTIC generated from the optimisation process and the cost savings realised between the conventional options for UWDS transitions on the option for transitioning based on the UWDS transition platform. The results of the sensitivity analysis are presented in Table 7-6.

Table 7-6: Results of sensitivity analyses for the TIC, LIC and BIC weights

Sno	**Variation of Weights**			**PTIC (£)**				**Life cycle costs**		**Savings**	
				UWDS transition platform		Without transition platform		UWDS Platform	No Platform		
	TIC	BIC	LIC	Phase 1	Phase 2	Phase 1	Phase 2				Amount
1	0.33	0.33	0.33	1.833E+06	1.944E+07	1.971E+06	2.096E+07	2.127E+07	2.293E+07	Yes	1.662E+06
2	1.00	-	-	1.938E+06	2.093E+07	2.012E+06	2.051E+07	2.287E+07	2.252E+07	No	-3.476E+05
3	0.01	0.99	-	1.998E+04	1.772E+05	1.563E+05	2.150E+05	1.971E+05	3.713E+05	Yes	1.742E+05
4	0.01	-	0.99	2.199E+04	2.264E+05	2.252E+04	2.327E+05	2.484E+05	2.552E+05	Yes	6.811E+03
5	0.01	0.50	0.50	1.883E+04	2.131E+03	1.815E+04	2.061E+05	2.320E+05	2.242E+05	No	-7.721E+03
6	0.50	-	0.50	1.009E+06	1.012E+07	1.007E+06	1.12E+07	1.113E+07	1.217E+07	Yes	1.046E+06
7	0.50	0.50	-	1.077E+06	1.034E+07	1.037E+06	1.063E+07	1.141E+07	1.167E+07	Yes	2.542E+05
Total per transition phase				5.918E+06	6.144E+07	6.224E+06	6.393E+07	Overall		2,788,135	
Total-Transition option				67,360,662			70,148,797				

The results show that the UWDS transition platform option provided the least future transition impact and maximum cost savings in the majority of the optimisations implemented for the different weight combinations considered. Based on the results of analysis of the sensitivity of the weights, it can be concluded that the UWDS transition platform option is more favourable with respect to enabling maximum cost saving and minimum transition impacts on future transitions of the UWDS in five out of seven cases of the weight variations. In addition, insignificant variation of the value of total PTIC irrespective of the weights used was observed. This implies that the influence of the weights of the attributes is not captured by the UWDS transition single objective formulation. Therefore, there is a need to consider applying a multi-objective UWDS transition formulation that can take care of the objectives of the attributes of the transition formulation.

CHAPTER EIGHT

CONCLUSIONS AND RECOMMENDATIONS

8. Introduction

Drawing from the definition of sustainability developed by the Brundtland Commission in a 1987 United Nations Report, upgrade of Urban Water Distribution Systems (UWDS) should not only meet the present requirements but should also embed in the UWDS the attribute of being able to be continuously transitioned at a minimal cost without lock-in. This was the impetus for designing for UWDS transitions. The main aim of this research was to develop methods to analyse cause-effect relationships of UWDS socio-technical transitions and to introduce transition impact costs into the existing models for the design and upgrade of UWDS. Specifically the aim supports decision makers in the analysis and identification of options for transitioning UWDS caused by global change pressures such as population growth and urbanization. The specific objectives of this study were:

- To develop a conceptual framework for designing for UWDS transitions and to review UWDS transitions, drivers and barriers;
- To develop a framework and approach to establish a relationship between household socio-economic characteristics and the transition between UWDS options;
- To develop an approach for evaluation of socio-economic impact due to the UWDS transition;
- To develop a methodology for designing for UWDS transitionability that departs from the conventional optimisation based upgrade approaches to considering technical impact costs, operation and maintenance impact costs such as leakage and burst costs and social impact costs based on the UWDS transition platform; and

- To test, examine and to analyse the sensitivity and performance of the developed approaches on two case studies based on two real urban water networks of Iganga Water and Kampala Water as a proof of concept.

Whereas the approaches, models and tools developed in this study have successively been applied on Rubaga Water Distribution Network (RWDN) in Rubaga Division, Kampala District and on Iganga UWDS (I-UWDS), Iganga; an emerging small town in Uganda, they can with basic modifications generically be applied to UWDS in developed and developing countries. This significance and contribution of the study are elaborated in Section 8.1.

8.1 Significance and Contribution of the Study

A review of the current approaches for the transitioning UWDS leads to the conclusion that; in order to design UWDS that do not constrain future transitions (lock-us in), tools, methods and approaches to evaluate the pros and cons of the UWDS transition options are required.

To a large extent, novel approaches to improve the evaluation, planning, design and management of UWDS transitions process have been proposed in the thesis. The approaches facilitate a better informed decision making process on how to upgrade existing UWDS not only based on operation and maintenance costs but also according to anticipated impacts such transitions would have on the future technical and socio-economic characteristics of UWDS and its environment. The originality and contribution of this thesis is in three theme areas: theoretical methodological and practical. With respect to the originality, the thesis has:

(i) Developed a conceptual framework for the analysis and assessment of the technical transition of UWDS that embeds the research in the existing academic context approaches (see Section 8.2.1).

(ii) Developed a novel SII framework based on the Multi Criteria Decision Analysis (MCDA) and the Analytical Hierarchical Process (AHP) to provide an estimate of the socio-economic impacts in an urban area due to UWDS transitions. This has been done by combining indicators at the Urban characteristic (UC), Urban Infrastructure (UI) and Socio-economic (SE) dimension (see Section 8.2.2). This framework determines the socio-economic input parameter used by UTIAM (see Section 8.2.2).

(iii) Developed an approach for modelling the relationship between socio-economic characteristics and UWDS options and the identification of the most significant socio-economic factors that are associated with the transition of UWDS (see Section 8.2.3).

(iv) Developed a novel UWDS transition design approach (UTIAM) that considers not only operation and maintenance costs (leakage and burst costs) but also anticipated impacts such transitions would have on the future technical and socio-economic characteristics of UWDS (PTIC). This important because it enhances decision making amidst scarce resources (see Section 8.2.4).

(v) Developed a novel pipe technical impact (TIC) assessment methodology. The methodology uses pipe prioritisation and optimisation models to estimate the relative importance of a pipe and group of incumbent pipes. TIC is based on the derivative of the cost of re-optimising pipes and pipe cohorts of the future UWDS composed of a platform of pipe stock of an incumbent system (see Section 8.2.4).

(vi) Established that the UWDS transition based on the product platform concept can be applied to UWDS to minimise future impact costs. Hence maximum cost savings can be achieved when UWDS upgrades are implemented with consideration of future transitionability.

(vii) Developed original detailed qualitative and quantitative case studies that is to say one with mature infrastructure in Chapter 7 and the other with infrastructure in its infancy in Chapter 6 that embed both technical and social aspects when upgrading UWDS (see Section 8.2.5).

Based on the objectives of the study presented in Chapter 1, the pros and cons of the proposed methodology for assessing modelling and designing for UWDS transitions as well as their testing on real world case studies are discussed in the section below.

8.2 Conclusions

This study focused on developing methods and techniques to model the relationship and consider minimisation of transition impacts such as technical impacts, operation and maintenance impacts, and social impacts during UWDS transitions. The developed transition models and techniques guide the underlying technical and socio-economic mechanisms of the long term continuous phased change from existing UWDS to an optimized future UWDS.

Novel approaches to: (i) Quantify socio-economic impacts; (ii) Model the relationship between socio-economic characteristics and UWDS transitions; and (iii) Design for UWDS transitions based on a measure of socio-economic and technical impacts have been developed. The findings, discussions and conclusions of the components of the study are outlined in the sections that follow.

8.2.1 Development of a Conceptual Framework for UWDS Transitions

In Chapter 2, a review of the existing theory and model relevant to the transitioning of UWDS was undertaken and research gaps identified. Based on the review, a conceptual framework that embeds the research in the existing academic context was formulated. The conclusions that can be made from the literature review performed in Chapter 2 revealed that:

- During the design for upgrade of UWDS, aspects that consider technical transition impact, socio-transition impact, quantification of socio-transition impacts and the relationship between socio-economic characteristics and the transition of UWDS are essential to understand and design for UWDS transitions.

- Existing decision models are not populated with data and lack well defined techniques for planning and analysis of future UWDS transitions. The models do not enable an understanding of the relationships and impact of the the different subsystems during the transitioning process. Although the relationship between the social system and technical system have been well established in the literature, few studies have attempted to quantitatively model the relationship between urban socio-economic characteristics, and the transition in UWDS options.
- Conventional approaches for computation of socio-economic impacts when upgrading UWDS are skewed towards post-design rather than pre-design exercise. While evaluation of socio-economic impacts due to the transition of UWDS is required because UWDS transitions are socio-technical, a methodology for the quantification of the impacts remains a work in progress.
- Whereas real options approach (ROA) is gaining widespread acceptance for valuation of infrastructure faced with changing future states, approaches to operationalise it for UWDS is still elusive.
- Even when good progress has been made in developing models and tools for UWDS, upgrades, these models are faced with a predicament. The consideration of the interactions between the socio-technical systems within these models is still a work in progress. Also existing models and or objective functions and penalty functions for UWDS are skewed towards only operation and maintenance costs without consideration of future transitionability. In this respect the product platform concept widely applied in other fields to facilitate changeability of the systems in the future has been reviewed to address the design for transitionability problem. However even when the benefits of the product platform concept are well documented, it has hardly been applied to the UWDS transition problem.

- Although not conclusive, it can be argued that this review acts as a starting point for engineering, planners and socio-economists interested in the UWDS transition problem in developing future research theme areas.

8.2.2 Development of framework to quantify Socio-Economic Impacts (SII)

A SII framework was developed (see Chapter 3) and validated on Kampala City and Iganga Municipality case studies as proof of concept to test the robustness of the of the developed approach. The approach is based around MCDA and aggregates indicators at three hierarchical levels while the allocation of weights within the framework is based on the AHP technique. The framework enables the determination of a metric for UWDS transition zone socio-economic impact indicator. The indicator was based on a systems approach that considers the impacts on the subsystems of the urban system which include the urban infrastructure system, urban characteristic system and the socio-economic system. The framework is suitable for areas with limited data availability. The qualitative data has been encoded from key experts. The following conclusions can be made from the methodology for quantification of SII proposed in Chapter 3.

- The methodology for quantification of SII provides a generic framework that can be used by water utilities and city authorities to quantify SEI for pipes and pipe cohorts. The framework is based on a single composite indicator. The methodology enables decision-makers in water utilities and city authorities to evaluate and prioritise UWDS transitions zones with high and low SEI. Based on the developed approach, options for transitioning UWDS that minimize SEI can be selected;
- A set of dimensions that capture the SEI of an UWDS transition on an urban area and its environment have been developed. The proposed dimensions are able to take care

of the following SEI categories: Urban Characteristic Impact (UC), the Urban Infrastructure Impact (UI) and Socio-economic Impact (SE);

- The dimensions that represent impacts in an urban area are able to distinguish between the following dimensions in an urban area: urban form, urban infrastructure and the wellbeing and standard of living of the communities. This is not the case for the impact indicators used by Dandy and Engelhardt (2001) and Tanyimboh and Kalungi (2008) in the long term upgrade of UWDS; and
- A limiting factor to the application of this framework for the assessment of SEI of pipes and pipe particularly for developing countries is that there exist uncertainties that impact the results of the model, such as the aggregation of dimensions and indicators using weights. The other limitation of the SII approach is that while it is suitable in data scarce scenarios, it is criticized for being subjective.

8.2.3 Modelling Socio-Technical Transitions

Modelling of socio-technical transition has received a relatively low attention for UWDS. The conclusions that can be made from the developed approach for modelling socio-technical transitions proposed in Chapter 4 include:

- Socio-economic characteristics such as residence, education level, wealth status, age of household, housing characteristics, type of toilet facility, floor material, wall material and roof material were shown to be significantly associated with the transition in UWDS options. Whereas electricity connection and type of toilet facility are the most significant socio-economic characteristics associated with the transition in UWDS options, the influence of these variables with regard to UWDS transition is not constant over time. In other words, one cannot adopt a constant model for the cause-effect relationship between UWDS transitions. Effective and continuous modelling of socio-technical UWDS transitions is recommended;

- Empirical models based on MNL are a suitable approach for analysis of how socio-technical characteristics influence UWDS transitions. The approach provides decision makers with the means to identify the most significant socio-economic characteristics that could be improved to overcome the barriers to UWDS transitions; and
- The limitation to the use of MNL is that the outcome of the model depends on the prior classifications and scores which are derived using a subjective process. Moreover, this condition is escalated by lack of accurate and sufficient data. To improve the reliability of the methodology, physically driven models that capture real time data solely generated for the MNL are recommended. However, procurement of software tools and staff to ensure collection of accurate real time physically based data may be economically unjustifiable. This is because; the potential benefits that accrue from the data improvement may not justify the additional cost required.

8.2.4 Designing for UWDS Transitions

The following conclusions can be made from the methodology for designing for UWDS Transitions proposed in Chapter 5.

- An approach for the design of UWDS transition (UTIAM) has been developed. The approach can be used by planners and engineers to take a new direction while designing for UWDS upgrade. The developed approach departs from the conventional approach to considering socio-economic impacts and transition impacts. This is required in today’s urban areas and cities where global change pressures such as urbanisation and population growth maker the procedure for the upgrade of UWDS uncertain. The transition design approach provides the additional advantage of transitionability to allow for minimisation of social and technical switching costs during the life cycle of the UWDS. The developed approach is particularly useful in developing countries where the infrastructure is in its infancy and water utilities are financially constrained. Chapter 5 has demonstrated that the transition design approach is possible and enables maximum cost savings in terms of transition impact costs

- A limitation of the developed approach is that the aggregation of TIC, OIC and SIC into a composite index using weights increases the uncertainty and reliability of the developed approach. However, it is argued that: (a) integration of socio-economic and technical impacts is more essential than an accurate mono analysis; and (b) the correctness of the weights and aggregation process was commensurate to the resource and time limitations
- While the performance of an UWDS can be characterised by both structural (geometric) and hydraulic properties, in this study, the computation of performance of an UWDS has been skewed towards hydraulic properties. This limitation necessitates reformulation of the optimisation problem with consideration of both geometric and hydraulic characteristics of the UWDS
- The methodology of transitioning an existing UWDS based on the platform concept is more cost effective than transitioning based on the conventional approach. Application of the developed approach on the hypothetical case study revealed that transitioning the UWDS based on the platform concept reduced the future transition lifecycle costs by about 10% in contrast to using the conventional approach;
- The incorporation of the expert preferences in UTIAM through the SII obtained in Chapter 3 means that: (a) the solutions are more acceptable to stakeholders than most conventional approaches; (b) SII influence the optimisation process; and (c) can

facilitate tailoring the developed transitions to the requirements of different stakeholders by making modifications to the stakeholders' objectives. To increase the reliability of the model and minimise the influence of subjectivity, statistical driven or data driven approaches should be explored;

- A set of attributes that capture the impacts of an UWDS transition (PTIC) have been developed. The proposed attributes are able to take care of socio-economic, technical as well as the conventional operation and maintenance transition impact costs on the future system. This departs from the conventional models for the upgrade of UWDS that are biased towards operation and maintenance costs. In relation to the existing approaches for upgrading UWDS, an integrated approach presents a comprehensive view to the UWDS transition process;
- The methodologies developed for identification of pipes with the least transition impact on the future UWDS based on prioritisation models and the two stage optimisation model based on the platform approach (Wei et al. 2008) provide a generic methodology. The methodology can be used by planners and engineers to identify pipes and pipe cohorts for transitioning with a relatively lower impact on the future UWDS; and
- The consideration of future uncertainties has been based on the scenario analysis technique because of time limitations. The future UWDS have been developed based on the world markets scenario (advocates high levels of economic growth). This is because its suits the current scenarios in urbanisation and populations growth.

8.2.5 Case Studies

To test the robustness of the developed approaches, it was important to validate the models of real life case studies of I-UWDS and RWDN both of which are under management of

National Water and Sewerage Corporation. The following conclusions can be made about the case study application:

- While results of the technical impact costs, SII, leakage impact costs and burst repair impact costs vary for the I-UWDS and RWDN, maximum cost savings of future transition impact were realised. The savings were realised when both case studies were transitioned based on the UWDS platform approach as compared to the conventional approach. Thus, the developed approaches and models can be applied for modelling and designing for UWDS transitions particularly in a developing country;
- The PTIC model has a relatively low sensitivity to variations in the unit cost of leakage, unit cost of burst repair costs and the weights for all the three transition phases irrespective of the RWDN transition option. Hence, the approach is efficient and effective in determining the most optimal option for transitioning the UWDS;
- A limitation is that the hydraulic analysis was carried out in a steady state whereby the demand variation is assumed constant throughout the analysis time. It is desirable to run the hydraulic analysis in the future based on a varying demand;
- Another limitation of the case study approach is that it has been based on only one future UWDS scenario. While this approach is suitable in data scarce scenarios, it is criticised for having uncertainties and being subjective;
- During the application of the UWDS transition approach to establish the most suitable options for transitioning UWDS on the hypothetical, RWDN and I-UWDS various assumptions and data used were obtained from literature due to data limitations. Therefore, there is a need to test the approach based on actual field data.

8.3 Recommendations for Future Research

Based on the aforementioned Sections 8.2.1.1-8.2.6, it can be concluded that the objectives of the study stated in Chapter 1 have been addressed with the developed frameworks, methodology for assessing modelling and designing for UWDS transitions. However, these have been based on a number of model assumptions and simplifications. Despite these limitations, the approach and can be used to take care of the future transitionability of the UWDS. Nonetheless questions and debates are generated that can only be answered through further research to refine the proposed methodology. These are presented below:

- Further research is required that considers the impact of geometric properties on the transitionability of an UWDS. Such a relationship; between geometric properties and UWDS have been studied by Yahaya (2010) Yazdani et al (2011) and Nemanja (2012), among others. However, they did not consider aspects of UWDS transition. The impact of the geometry on the transition of UWDS can be evaluated and incorporated in the developed UWDS transition methodology;
- Because the function of the developed multi-objective problem was converted into as a single-objective problem (PTIC) based on the assumption of a linear relationship between SIC and TIC, further studies should be undertaken to identify a suitable function from a suite of functions: linear, convex, constant and concave to represent the relationship between SIC and TIC in the transition of UWDS. In addition, the multi-objective approach should be considered to improve the effectiveness of the model;
- In determining weights for the SII: UC, UI and SE, the AHP approach has been applied. It would beneficial to compare the results of the AHP methods with other methods such as PROMETHEE and to ascertain the most suitable for assessment of

SII. Hence better methods of obtaining parameters from the field should be considered too;

- Further research is required with respect to the use of data driven models based on the physical characteristics of the urban environment to determine the SII and to model the relationship between socio-economic characteristics and the transition of UWDS. The models developed could be integrated into a GIS platform that facilitates good, easy data management and regular update of records. Modelling the dynamics of urban characteristics based on Geographical Information System (GIS) based cellular automata has been studied by Batty et al (1999). Hence SII and the relationship between SE and the transition between can be accessed through GIS based on cellular automata;
- Although UWDS transitions are outcome of the interaction between the technical, institutional and socio-economic system, the developed UWDS transition model has only considered the interaction between socio-economic and technical subsystems. There is need to develop a model that captures the feedback , interrelationships and interactions between the sub-systems of technical, institutional and socio-economic system. To this extent, agent based models could be used to simulate the interaction between the subsystems engaged in the UWDS transition process;
- To simulate future UWDS transition strategies, the number of nodes, the nodal demand and pipe length were increased based on a deterministic approach which was used as an input to the model. To improve the results of the model, better approaches could be applied to model the uncertainty of the demand and urban growth based on probabilistic methods;
- Though it is not appropriate to make generalisations derived from just a single research study coupled with two case study applications on the Iganga and Kampala,

some research findings may be applicable to the UWDS transition problem particularly in developing countries where the opportunity for growth is the greatest. Therefore, to increase the evidence base for the proposed approach, more case studies are required. Furthermore there is a need to actually test the developed approaches on a few UWDS;

- Whereas the case studies have been implemented based on the world markets scenario that assumes globalisation and urbanisation growth. It is recommended that the reliability and effectiveness of the proposed approach can be enhanced by considering the remaining UK foresight future scenarios of world markets, local stewardship and provincial enterprise that recognise the influences of the different scenarios on the performance of the model;
- The study uses selected parameters to quantify social and technical impacts due to UWDS transitions based on socio-economic impacts costs due to UWDS transitions, leakage impact costs, technical impact costs and burst impact costs. It is recommended that the transition impact formulation is extended to cater for energy costs including pumps and the energy component of leakage and burst repair. This resonates with (Savic et al. 1997) call to optimise the scheduling of pumps to achieve the maximum cost savings; and

- In solving the formulation for UWDS transition impact costs, this study uses equal weights to relate attributes of the formulation. While the attributes of the formulation are not sensitive to the weights, this may not be the case all the time. Therefore, there is a need to develop weights to relate the different attributes of the transition impact formulation. These weights could be developed using multi-criteria such as the AHP and PROMETHEE approaches widely applied in literature.

Based on the study coupled with two case study applications on Iganga and Kampala Districts, maximum cost savings on future transition impact costs can be realised when existing UWDS are upgraded based on UWDS transition platform and consideration of future UWDS transitionability as compared to the conventional approach. From an industrial and business perspective to enhance UWDS sustainability, the approach can enable engineers and planners to of urban water utilities to minimise UWDS transition costs by identifying the UWDS transition platform of the existing UWDS that has the least impact on future UWDS.

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Appendices

Appendix- A: Socio-economic Impact indicator & AHP

A-1: The judgement matrix for the sub criteria level

		SYNTHESIS OF RESULTS FROM EXPERTS-JUDGEMENT MATRIX																																				Consistsence				
		Plannners												Engineers												Social-Economist												Planners				
Subject Expert	Sub Criteria	Level of urban development [SC-1]	Type of Roofing Material [SC-2]	Material for Walls [SC-3]	Floor material [SC-4]	% Built up area [1-low 5-High] [SC-5]	Sanitation/Sewerage system [SC-6]	Urban darinage/Sewerage [SC-7]	Urban Water System [SC-8]	Roads	Wealth Index [SC-10]	Population density [SC-11]	Level of education [SC-12]	Level of urban development [SC-1]	Type of Roofing Material [SC-2]	Material for Walls [SC-3]	Floor material [SC-4]	% Built up area [1-low 5-High] [SC-5]	Sanitation/Sewerage system [SC-6]	Urban darinage/Sewerage [SC-7]	Urban Water System [SC-8]	Roads	Wealth Index [SC-10]	Population density [SC-11]	Level of education [SC-12]	Level of urban development [SC-1]	Type of Roofing Material [SC-2]	Material for Walls [SC-3]	Floor material [SC-4]	% Built up area [1-low 5-High] [SC-5]	Sanitation/Sewerage system [SC-6]	Urban darinage/Sewerage [SC-7]	Urban Water System [SC-8]	Roads	Wealth Index [SC-10]	Population density [SC-11]	Level of education [SC-12]	Priority Vector	Weighted Sum Vector	Consistence vector	Consistence Index	Consistence Ratio
Planners	Level of urban development [SC-1]	1.00	1.00	2.00	3.00	5.00																																0.33	1.69	5.07	0.01	0.01
	Type of Roofing Material [SC-2]	1.00	1.00	2.00	4.00	3.00																																0.32	1.60	5.06	0.01	0.01
	Material for Walls [SC-3]	0.50	0.50	1.00	3.00	2.00																																0.18	0.93	5.06	0.01	0.01
	Floor material [SC-4]	0.33	0.25	0.33	1.00	1.00																																0.08	0.42	5.05	0.01	0.01
	% Built up area [1-low 5-High] [SC-5]	0.20	0.33	0.50	1.00	1.00																																0.09	0.43	5.06	0.01	0.01
	Sanitation/Sewerage system [SC-6]						1.00	4.00	1.00	3.00																												0.38	1.63	4.33	0.01	0.01
	Urban darinage/Sewerage [SC-7]						0.25	1.00	0.33	5.00																												0.17	0.67	3.87	0.01	0.01
	Urban Water System [SC-8]						1.00	3.00	1.00	6.00																												0.40	1.62	4.09	0.01	0.01
	Roads [SC-9]						0.14	0.20	0.17	1.00																												0.05	0.21	3.84	0.01	0.01
	Wealth Index [SC-10]										1.00	2.00	7.00																									0.58	1.77	3.05	0.02	0.03
	Population density [SC-11]										0.50	1.00	6.00																									0.35	1.06	3.04	0.02	0.03
	Level of education [SC-12]										0.14	0.17	1.00																									0.07	0.21	3.01	0.02	0.03
Engineers	Level of urban development [SC-1]													1.00	1.00	2.00	3.00	5.00																				0.33	1.69	5.07	0.01	0.01
	Type of Roofing Material [SC-2]													1.00	1.00	2.00	4.00	3.00																				0.32	1.60	5.06	0.01	0.01
	Material for Walls [SC-3]													0.50	0.50	1.00	3.00	2.00																				0.18	0.93	5.06	0.01	0.01
	Floor material [SC-4]													0.33	0.25	0.33	1.00	1.00																				0.08	0.42	5.05	0.01	0.01
	% Built up area [1-low 5-High] [SC-5]													0.20	0.33	0.50	1.00	1.00																				0.09	0.43	5.06	0.01	0.01
	Sanitation/Sewerage system [SC-6]																		1.00	4.00	1.00	3.00																0.38	1.63	4.33	0.01	0.01
	Urban darinage/Sewerage [SC-7]																		0.25	1.00	0.33	5.00																0.17	0.67	3.87	0.01	0.01
	Urban Water System [SC-8]																		1.00	3.00	1.00	6.00																0.40	1.62	4.09	0.01	0.01
	Roads [SC-9]																		0.14	0.20	0.17	1.00																0.05	0.21	3.84	0.01	0.01
	Wealth Index [SC-10]																						1.00	3.00	9.00													0.66	2.04	3.10	0.03	0.05
	Population density [SC-11]																						0.33	1.00	6.00													0.28	0.86	3.05	0.03	0.05
	Level of education [SC-12]																						0.11	0.17	1.00													0.06	0.18	3.01	0.03	0.05
Social Economists	Level of urban development [SC-1]																									1.00	1.00	2.00	3.00	5.00								0.33	1.69	5.07	0.01	0.01
	Type of Roofing Material [SC-2]																									1.00	1.00	2.00	4.00	3.00								0.32	1.60	5.06	0.01	0.01
	Material for Walls [SC-3]																									0.50	0.50	1.00	3.00	2.00								0.18	0.93	5.06	0.01	0.01
	Floor material [SC-4]																									0.33	0.25	0.33	1.00	1.00								0.08	0.42	5.05	0.01	0.01
	% Built up area [1-low 5-High] [SC-5]																									0.20	0.33	0.50	1.00	1.00								0.09	0.43	5.06	0.01	0.01
	Sanitation/Sewerage system [SC-6]																														1.00	5.00	3	7.00				0.54	2.39	4.40	0.08	0.09
	Urban darinage/Sewerage [SC-7]																														0.20	1.00	0.33	5.00				0.14	0.58	4.14	0.08	0.09
	Urban Water System [SC-8]																														0.33	3	1.00	6				0.27	1.17	4.39	0.08	0.09
	Roads [SC-9]																														0.14	0.20	0.17	1.00				0.05	0.20	4.06	0.08	0.09
	Wealth Index [SC-10]																																		1.00	3.00	8.00	0.65	2.03	3.14	0.04	0.06
	Population density [SC-11]																																		0.33	1.00	6.00	0.29	0.89	3.07	0.04	0.06
	Level of education [SC-12]																																		0.13	0.17	1.00	0.06	0.19	3.01	0.04	0.06
Total	Level of urban development [SC-1]																																					0.33			0.41	0.14
	Type of Roofing Material [SC-2]																																					0.32				0.13
	Material for Walls [SC-3]																																					0.18				0.07
	Floor material [SC-4]																																					0.08				0.03
	% Built up area [1-low 5-High] [SC-5]																																					0.09				0.03
	Sanitation/Sewerage system [SC-6]																																					0.43			0.32	0.14
	Urban darinage/Sewerage [SC-7]																																					0.16				0.05
	Urban Water System [SC-8]																																					0.35				0.11
	Roads [SC-9]																																					0.05				0.02
	Wealth Index [SC-10]																																					0.63			0.27	0.17
	Population density [SC-11]																																					0.31				0.08
	Level of education [SC-12]																																					0.06				0.02

Dear Sir/Madam

Socio-economic Impact Indicator Criteria and Sub Criteria Weights

This questionnaire is part of a PhD study whose case studies are being conducted in and around Kampala City Council and Iganga Municipal Council. The purpose of the study is to develop approaches for transitioning Urban Water Distribution Systems that consider both technical and socio-economic impacts.

The questions are designed to help us identify and rank weights for criteria and sub criteria for socio-economic impact indicators due to the transition of urban water distribution systems. It's in that respect that I kindly request you to provide the relative important of the different criteria and sub criteria for the socio-economic impact indicator.
We will be very careful not to disclose your individual identity but general information is required to enable us to organize the data more logically and more usefully.

Please if you feel that some useful concern has been left out of the questionnaire, the interviewer will be happy to record your comments.

Kind Regards

Jotham Sempewo
PhD Student
School of Civil Engineering| University of Birmingham

SECTION 1: Area of expertise

Sno	Subject Expert	Tick profession that applies to you
1	Planner	☐
2	Engineer	☐
3	Social Economist	☐

SECTION 2: Criteria Weights

Based on your experience what is the relative importance of the socio-economic impact indicator criteria.

Criteria	How important is criteria on left compared to criteria on right 1=Equally important;3=Moderately important; 5=Strong Important;7=Very Strong importance; 9= Extremely important. Please circle																	Criteria
	Increasing importance of criteria on left								Equal	Increasing importance of criteria on right								
Urban Characteristic Impact	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Urban Characteristic Impact
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Urban Infrastructure Impact
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Socio-economic Impact
Urban Infrastructure Impact	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Urban Infrastructure Impact
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Urban Characteristic Impact
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Socio-economic Impact
Socio-economic Impact	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Socio-economic Impact
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Urban Infrastructure Impact
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Urban Characteristic Impact

SECTION 2.1: Sub Criteria Weights

2.1.1 Comparison Urban characteristic sub-criteria

Comparison Urban characteristic sub-criteria																		
Criteria	How imprtant is criteria on left compared to criteria on right 1=Equally important;3=Moderately important; 5=Strong Important;7=Very Strong importantance; 9= Extremely important. Please circle																	Sub-criteria
	Increasing importance of criteria on left								Equal	Increasing importance of criteria on right								
Level of urban development	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Level of urban development
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Type of Roofing Material
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Material for Walls
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Floor material
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	% Built up area
Type of Roofing Material	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Type of Roofing Material
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Level of urban development
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Material for Walls
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Floor material
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	% Built up area
Material for Walls	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Material for Walls
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Level of urban development
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Type of Roofing Material
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Floor material
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	% Built up area
Floor material	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Floor material
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Type of Roofing Material
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Level of urban development
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Material for Walls
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	% Built up area
% Built up area	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	% Built up area
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Floor material
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Type of Roofing Material
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Level of urban development
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Material for Walls

2.1.2 Comparison Urban Infrastructure sub-criteria

Comparison Urban Infrastructure sub criteria																		
Criteria	How important is criteria on left compared to criteria on right 1=Equally important;3=Moderately important; 5=Strong Important;7=Very Strong importance; 9= Extremely important. Please circle appropriate circle																	Sub-criteria
	← Increasing importance of criteria on left								Equal	→ Increasing importance of criteria on right								
Sanitation/ Sewerage system	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Sanitation /Sewerage system
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Urban drainage /Sewerage
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Urban Water System
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Roads
Urban drainage/ Sewerage	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Urban drainage /Sewerage
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Sanitation /Sewerage system
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Urban Water System
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Roads
Urban Water System	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Urban Water System
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Sanitation/Sewerage system
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Urban drainage/Sewerage
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Roads
Roads	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Roads
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Sanitation /Sewerage system
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Urban drainage/Sewerage
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Urban Water System

2.1.3 Comparison socio-economic sub-criteria

Comparison Socio-economic sub-criteria																		
Criteria	How important is criteria on left compared to criteria on right 1=Equally important;3=Moderately important; 5=Strong Important;7=Very Strong importance; 9= Extremely important. Please circle appropriate circle																	Sub-criteria
	← Increasing importance of criteria on left								Equal	→ Increasing importance of criteria on right								
Wealth Index	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Wealth Index
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Population density
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Local Economy
Population density	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Population density
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Wealth Index
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Local Economy

Local Economy	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Local Economy
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Wealth Index
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Population density

SECTION 3: Scoring the different UWDS transition Zones

Sno	Subject expert	Tick profession that applies to you
1	Planner	☐
2	Engineer	☐
3	Social Economist	☐

3.1 Scoring the UWDS transition Zones Location: ....

Criteria	Sub Criteria	Based on you background experience and the characterisation of criteria and sub criteria [Table 4.7] Score the different UWDS transition Zones						
		UWDS transition Zones						
		1	2	3	4	5	6	7
Urban Characteristic Impact [UC]	Level of urban development							
	Type of Roofing Material							
	Material for Walls							
	Floor material							
	% Built up area [1-low 5-High]							
Urban Infrastructure Impact [UI]	Sanitation/Sewerage system							
	Urban drainage/Sewerage							
	Urban Water System							
	Roads							
Socio-economic Impact [SE]	Wealth Index							
	Population density							
	Level of education							

Appendix- B : Stata output for Multinomial Logistic Regression

B-1: Strata output for Multinomial Logistic Regression

```
------------------------------------------------------------------------
name:  < Modeling  socio-economic characteristics and  transition in  UWDS
options>
       log:  C:\Users\Circuit City\Documents\PERSONAL
DOCUMENTS\udhs2007\Plan
o
> f Analysis 22 June 2012.smcl
  log type:  smcl
 opened on:  23 Jun 2012, 21:38:27

.
. ********Variable Description******
.
. d v101 v102 v149 v190 v136 v151 v152 v119 v116 v127 v128 v129

              storage  display     value
variable name   type   format      label      variable label
-------------------------------------------------------------------------
---
--
v101           double %10.0g      v101       region
v102           double %10.0g      v102       type of place of residence
v149           double %10.0g      v149       educational attainment
v190           double %10.0g      v190       wealth index
v136           double %10.0g                 number of household members
v151           double %10.0g      v151       sex of household head
v152           double %10.0g      v152       age of household head
v119           double %10.0g      v119       has electricity
v116           double %10.0g      v116       type of toilet facility
v127           double %10.0g      v127       main floor material
v128           double %10.0g      v128       main wall material
v129           double %10.0g      v129       main roof material

.
. *********Distribution of Water Sources*******
. tab     source

                 source |      Freq.     Percent        Cum.
------------------------+-----------------------------------
       Piped in house  |        253       15.59       15.59
Yard Taps & standpipes |        413       25.45       41.04
      Improved Sources |        747       46.03       87.06
     Uniproved Sources |        210       12.94      100.00
------------------------+-----------------------------------
                  Total |      1,623      100.00

.
. tab     v101

      region |      Freq.     Percent        Cum.
```

```
-------------+-----------------------------------
     kampala |        846       48.23       48.23
east central |        908       51.77      100.00
-------------+-----------------------------------
       Total |      1,754      100.00

. tab     v102

    type of |
   place of |
  residence |      Freq.     Percent        Cum.
------------+-----------------------------------
      urban |        912       52.00       52.00
      rural |        842       48.00      100.00
------------+-----------------------------------
      Total |      1,754      100.00

. tab     v190

     wealth |
      index |      Freq.     Percent        Cum.
------------+-----------------------------------
    poorest |         90        5.13        5.13
     poorer |        164        9.35       14.48
     middle |        178       10.15       24.63
     richer |        317       18.07       42.70
    richest |      1,005       57.30      100.00
------------+-----------------------------------
      Total |      1,754      100.00

. tab     new_v149

  RECODE of |
       v149 |
(educationa |
          l |
attainment) |      Freq.     Percent        Cum.
------------+-----------------------------------
       None |        165        9.41        9.41
    Primary |        842       48.00       57.41
  Secondary |        584       33.30       90.71
     Higher |        163        9.29      100.00
------------+-----------------------------------
      Total |      1,754      100.00

. tab     new_v136

  RECODE of |
       v136 |
 (number of |
  household |
   members) |      Freq.     Percent        Cum.
------------+-----------------------------------
        1-4 |        560       31.93       31.93
        5-9 |        904       51.54       83.47
   10 Above |        290       16.53      100.00
------------+-----------------------------------
```

```
      Total |      1,754      100.00

. tab     v151

     sex of |
  household |
       head |      Freq.     Percent        Cum.
------------+-----------------------------------
       male |      1,155       65.85       65.85
     female |        599       34.15      100.00
------------+-----------------------------------
      Total |      1,754      100.00

. tab     new_v152

  RECODE of |
  v152 (age |
         of |
  household |
      head) |      Freq.     Percent        Cum.
------------+-----------------------------------
   Below 29 |        392       22.35       22.35
      30-39 |        606       34.55       56.90
      40-49 |        394       22.46       79.36
   Above 50 |        362       20.64      100.00
------------+-----------------------------------
      Total |      1,754      100.00

. tab     v119

    has electricity |      Freq.     Percent        Cum.
--------------------+-----------------------------------
                 no |      1,212       69.30       69.30
                yes |        537       30.70      100.00
--------------------+-----------------------------------
              Total |      1,749      100.00

. tab     new_v116

  RECODE of |
 v116 (type |
  of toilet |
  facility) |      Freq.     Percent        Cum.
------------+-----------------------------------
      Flush |        140        8.62        8.62
Pit Latrine |      1,288       79.26       87.88
        VIP |        134        8.25       96.12
      Other |         63        3.88      100.00
------------+-----------------------------------
      Total |      1,625      100.00

. tab     new_v127

RECODE of v127 |
   (main floor |
     material) |      Freq.     Percent        Cum.
---------------+-----------------------------------
```

```
 Natural/Earth |        694       42.79       42.79
Finished/Tiles |         64        3.95       46.73
        Cement |        864       53.27      100.00
---------------+-----------------------------------
         Total |      1,622      100.00

. tab     new_v128

  RECODE of v128 (main |
        wall material) |      Freq.     Percent        Cum.
-----------------------+-----------------------------------
   Natural/Rudimentary |        653       40.26       40.26
Finished/Cement blocks |        952       58.69       98.95
                 Other |         17        1.05      100.00
-----------------------+-----------------------------------
                 Total |      1,622      100.00

. tab     new_v129

     RECODE of v129 |
         (main roof |
          material) |      Freq.     Percent        Cum.
--------------------+-----------------------------------
Natural/Rudimentary |        278       17.11       17.11
        Iron Sheets |      1,268       78.03       95.14
    Tiles/Asbestors |         79        4.86      100.00
--------------------+-----------------------------------
              Total |      1,625      100.00

. tab     v153

      has telephone |      Freq.     Percent        Cum.
--------------------+-----------------------------------
                 no |      1,558       95.94       95.94
                yes |         66        4.06      100.00
--------------------+-----------------------------------
              Total |      1,624      100.00

.
. *********Distribution of Water Sources by Socio-economic Xtics*******
. tab     v101 source, row column chi2

+-------------------+
| Key               |
|-------------------|
|     frequency     |
|  row percentage   |
| column percentage |
+-------------------+

             |                   source
      region | Piped in   Yard Taps  Improved   Uniproved |      Total
-------------+--------------------------------------------+----------
     kampala |       240        364        122         53 |       779
             |     30.81      46.73      15.66       6.80 |    100.00
             |     94.86      88.14      16.33      25.24 |     48.00
-------------+--------------------------------------------+----------
```

```
east central |        13         49        625        157 |       844 
             |      1.54       5.81      74.05      18.60 |    100.00 
             |      5.14      11.86      83.67      74.76 |     52.00 
-------------+--------------------------------------------+----------
       Total |       253        413        747        210 |     1,623 
             |     15.59      25.45      46.03      12.94 |    100.00 
             |    100.00     100.00     100.00     100.00 |    100.00 

          Pearson chi2(3) = 832.8637   Pr = 0.000

. tab     v102 source, row column chi2

+-------------------+
| Key               |
|-------------------|
|     frequency     |
|  row percentage   |
| column percentage |
+-------------------+

   type of |
  place of |                   source
 residence | Piped in   Yard Taps  Improved   Uniproved |     Total
-----------+--------------------------------------------+----------
     urban |       253        398        130         58 |       839 
           |     30.15      47.44      15.49       6.91 |    100.00 
           |    100.00      96.37      17.40      27.62 |     51.69 
-----------+--------------------------------------------+----------
     rural |         0         15        617        152 |       784 
           |      0.00       1.91      78.70      19.39 |    100.00 
           |      0.00       3.63      82.60      72.38 |     48.31 
-----------+--------------------------------------------+----------
     Total |       253        413        747        210 |     1,623 
           |     15.59      25.45      46.03      12.94 |    100.00 
           |    100.00     100.00     100.00     100.00 |    100.00 

          Pearson chi2(3) = 966.9973   Pr = 0.000

. tab     v190 source, row column chi2

+-------------------+
| Key               |
|-------------------|
|     frequency     |
|  row percentage   |
| column percentage |
+-------------------+

    wealth |                   source
     index | Piped in   Yard Taps  Improved   Uniproved |     Total
-----------+--------------------------------------------+----------
   poorest |         0          0         63         24 |        87 
           |      0.00       0.00      72.41      27.59 |    100.00 
           |      0.00       0.00       8.43      11.43 |      5.36 
-----------+--------------------------------------------+----------
    poorer |         0          0        125         34 |       159 
           |      0.00       0.00      78.62      21.38 |    100.00 
```

```
           |      0.00       0.00      16.73      16.19 |      9.80 
-----------+--------------------------------------------+----------
    middle |         0          3        129         41 |       173 
           |      0.00       1.73      74.57      23.70 |    100.00 
           |      0.00       0.73      17.27      19.52 |     10.66 
-----------+--------------------------------------------+----------
    richer |         0         26        216         41 |       283 
           |      0.00       9.19      76.33      14.49 |    100.00 
           |      0.00       6.30      28.92      19.52 |     17.44 
-----------+--------------------------------------------+----------
   richest |       253        384        214         70 |       921 
           |     27.47      41.69      23.24       7.60 |    100.00 
           |    100.00      92.98      28.65      33.33 |     56.75 
-----------+--------------------------------------------+----------
     Total |       253        413        747        210 |     1,623 
           |     15.59      25.45      46.03      12.94 |    100.00 
           |    100.00     100.00     100.00     100.00 |    100.00 

          Pearson chi2(12) = 718.9410   Pr = 0.000

. tab     new_v149 source, row column chi2

+-------------------+
| Key               |
|-------------------|
|     frequency     |
|  row percentage   |
| column percentage |
+-------------------+

 RECODE of |
      v149 |
(education |
        al |
attainment |                   source
         ) | Piped in   Yard Taps  Improved   Uniproved |     Total
-----------+--------------------------------------------+----------
      None |         5         18        107         30 |       160 
           |      3.13      11.25      66.88      18.75 |    100.00 
           |      1.98       4.36      14.32      14.29 |      9.86 
-----------+--------------------------------------------+----------
   Primary |        71        152        443        120 |       786 
           |      9.03      19.34      56.36      15.27 |    100.00 
           |     28.06      36.80      59.30      57.14 |     48.43 
-----------+--------------------------------------------+----------
 Secondary |       105        194        173         52 |       524 
           |     20.04      37.02      33.02       9.92 |    100.00 
           |     41.50      46.97      23.16      24.76 |     32.29 
-----------+--------------------------------------------+----------
    Higher |        72         49         24          8 |       153 
           |     47.06      32.03      15.69       5.23 |    100.00 
           |     28.46      11.86       3.21       3.81 |      9.43 
-----------+--------------------------------------------+----------
     Total |       253        413        747        210 |     1,623 
           |     15.59      25.45      46.03      12.94 |    100.00 
           |    100.00     100.00     100.00     100.00 |    100.00 
```

```
          Pearson chi2(9) = 297.2729   Pr = 0.000

. tab     new_v136 source, row column chi2

+-------------------+
| Key               |
|-------------------|
|     frequency     |
|  row percentage   |
| column percentage |
+-------------------+

 RECODE of |
      v136 |
(number of |
 household |                    source
  members) | Piped in   Yard Taps  Improved   Uniproved |     Total
-----------+--------------------------------------------+----------
       1-4 |        76        173        221         64 |       534 
           |     14.23      32.40      41.39      11.99 |    100.00 
           |     30.04      41.89      29.59      30.48 |     32.90 
-----------+--------------------------------------------+----------
       5-9 |       141        190        405        111 |       847 
           |     16.65      22.43      47.82      13.11 |    100.00 
           |     55.73      46.00      54.22      52.86 |     52.19 
-----------+--------------------------------------------+----------
  10 Above |        36         50        121         35 |       242 
           |     14.88      20.66      50.00      14.46 |    100.00 
           |     14.23      12.11      16.20      16.67 |     14.91 
-----------+--------------------------------------------+----------
     Total |       253        413        747        210 |     1,623 
           |     15.59      25.45      46.03      12.94 |    100.00 
           |    100.00     100.00     100.00     100.00 |    100.00 

          Pearson chi2(6) =  21.4037   Pr = 0.002

. tab     v151 source, row column chi2

+-------------------+
| Key               |
|-------------------|
|     frequency     |
|  row percentage   |
| column percentage |
+-------------------+

    sex of |
 household |                    source
      head | Piped in   Yard Taps  Improved   Uniproved |     Total
-----------+--------------------------------------------+----------
      male |       157        244        516        158 |     1,075 
           |     14.60      22.70      48.00      14.70 |    100.00 
           |     62.06      59.08      69.08      75.24 |     66.24 
-----------+--------------------------------------------+----------
    female |        96        169        231         52 |       548 
           |     17.52      30.84      42.15       9.49 |    100.00 
           |     37.94      40.92      30.92      24.76 |     33.76 
```

```
-----------+--------------------------------------------+----------
     Total |       253        413        747        210 |     1,623 
           |     15.59      25.45      46.03      12.94 |    100.00 
           |    100.00     100.00     100.00     100.00 |    100.00 

          Pearson chi2(3) =  21.7383   Pr = 0.000

. tab     new_v152 source, row column chi2

+-------------------+
| Key               |
|-------------------|
|     frequency     |
|  row percentage   |
| column percentage |
+-------------------+

 RECODE of |
 v152 (age |
        of |
 household |                   source
     head) | Piped in   Yard Taps  Improved   Uniproved |     Total
-----------+--------------------------------------------+----------
  Below 29 |        43        118        158         51 |       370 
           |     11.62      31.89      42.70      13.78 |    100.00 
           |     17.00      28.57      21.15      24.29 |     22.80 
-----------+--------------------------------------------+----------
     30-39 |        92        170        242         61 |       565 
           |     16.28      30.09      42.83      10.80 |    100.00 
           |     36.36      41.16      32.40      29.05 |     34.81 
-----------+--------------------------------------------+----------
     40-49 |        59         74        201         44 |       378 
           |     15.61      19.58      53.17      11.64 |    100.00 
           |     23.32      17.92      26.91      20.95 |     23.29 
-----------+--------------------------------------------+----------
  Above 50 |        59         51        146         54 |       310 
           |     19.03      16.45      47.10      17.42 |    100.00 
           |     23.32      12.35      19.54      25.71 |     19.10 
-----------+--------------------------------------------+----------
     Total |       253        413        747        210 |     1,623 
           |     15.59      25.45      46.03      12.94 |    100.00 
           |    100.00     100.00     100.00     100.00 |    100.00 

          Pearson chi2(9) =  45.9930   Pr = 0.000

. tab     v119 source, row column chi2

+-------------------+
| Key               |
|-------------------|
|     frequency     |
|  row percentage   |
| column percentage |
+-------------------+

                    |                   source
```

```
    has electricity | Piped in   Yard Taps  Improved   Uniproved |
Total
--------------------+--------------------------------------------+--------
--
                 no |        37        186        677        181 |
1,081
                    |      3.42      17.21      62.63      16.74 |
100.00
                    |     14.62      45.04      90.87      87.44 |
66.81
--------------------+--------------------------------------------+--------
--
                yes |       216        227         68         26 |
537
                    |     40.22      42.27      12.66       4.84 |
100.00
                    |     85.38      54.96       9.13      12.56 |
33.19
--------------------+--------------------------------------------+--------
--
              Total |       253        413        745        207 |
1,618
                    |     15.64      25.53      46.04      12.79 |
100.00
                    |    100.00     100.00     100.00     100.00 |
100.00

          Pearson chi2(3) = 633.2903   Pr = 0.000

. tab     new_v116 source, row column chi2

+-------------------+
| Key               |
|-------------------|
|     frequency     |
|  row percentage   |
| column percentage |
+-------------------+

  RECODE of |
 v116 (type |
  of toilet |                      source
  facility) | Piped in   Yard Taps  Improved   Uniproved |     Total
------------+--------------------------------------------+----------
      Flush |       117         18          2          3 |       140 
            |     83.57      12.86       1.43       2.14 |    100.00 
            |     46.25       4.36       0.27       1.43 |      8.63 
------------+--------------------------------------------+----------
Pit Latrine |       102        338        670        176 |     1,286 
            |      7.93      26.28      52.10      13.69 |    100.00 
            |     40.32      81.84      89.69      83.81 |     79.24 
------------+--------------------------------------------+----------
        VIP |        34         57         34          9 |       134 
            |     25.37      42.54      25.37       6.72 |    100.00 
            |     13.44      13.80       4.55       4.29 |      8.26 
------------+--------------------------------------------+----------
      Other |         0          0         41         22 |        63 
```

```
            |      0.00       0.00      65.08      34.92 |     100.00
            |      0.00       0.00       5.49      10.48 |       3.88
------------+--------------------------------------------+----------
      Total |       253        413        747        210 |      1,623
            |     15.59      25.45      46.03      12.94 |     100.00
            |    100.00     100.00     100.00     100.00 |     100.00

          Pearson chi2(9) = 650.8732   Pr = 0.000

. tab     new_v127 source, row column chi2

+-------------------+
| Key               |
|-------------------|
|     frequency     |
|  row percentage   |
| column percentage |
+-------------------+

RECODE of v127 |
   (main floor |                    source
     material) | Piped in   Yard Taps  Improved   Uniproved |     Total
---------------+--------------------------------------------+----------
 Natural/Earth |         6         47        503        138 |       694
               |      0.86       6.77      72.48      19.88 |    100.00
               |      2.37      11.38      67.61      65.71 |     42.84
---------------+--------------------------------------------+----------
Finished/Tiles |        49          5          4          6 |        64
               |     76.56       7.81       6.25       9.38 |    100.00
               |     19.37       1.21       0.54       2.86 |      3.95
---------------+--------------------------------------------+----------
        Cement |       198        361        237         66 |       862
               |     22.97      41.88      27.49       7.66 |    100.00
               |     78.26      87.41      31.85      31.43 |     53.21
---------------+--------------------------------------------+----------
         Total |       253        413        744        210 |     1,620
               |     15.62      25.49      45.93      12.96 |    100.00
               |    100.00     100.00     100.00     100.00 |    100.00

          Pearson chi2(6) = 710.0606   Pr = 0.000

. tab     new_v128 source, row column chi2

+-------------------+
| Key               |
|-------------------|
|     frequency     |
|  row percentage   |
| column percentage |
+-------------------+

 RECODE of v128 (main |                    source
      wall material) | Piped in   Yard Taps  Improved   Uniproved |
Total
----------------------+--------------------------------------------+------
---
-
```

```
  Natural/Rudimentary |        26         95        416        114 |
651
                      |      3.99      14.59      63.90      17.51 |
100.00
                      |     10.32      23.06      55.76      54.29 |
40.19
----------------------+--------------------------------------------+------
---
-
Finished/Cement block |       222        308        327         95 |
952
                      |     23.32      32.35      34.35       9.98 |
100.00
                      |     88.10      74.76      43.83      45.24 |
58.77
----------------------+--------------------------------------------+------
---
-
                Other |         4          9          3          1 |
17
                      |     23.53      52.94      17.65       5.88 |
100.00
                      |      1.59       2.18       0.40       0.48 |
1.05
----------------------+--------------------------------------------+------
---
-
                Total |       252        412        746        210 |
1,620
                      |     15.56      25.43      46.05      12.96 |
100.00
                      |    100.00     100.00     100.00     100.00 |
100.00

          Pearson chi2(6) = 240.5113   Pr = 0.000

. tab     new_v129 source, row column chi2

+-------------------+
| Key               |
|-------------------|
|     frequency     |
|  row percentage   |
| column percentage |
+-------------------+

     RECODE of v129 |
         (main roof |                   source
          material) | Piped in   Yard Taps  Improved   Uniproved |
Total
--------------------+--------------------------------------------+--------
--
Natural/Rudimentary |         0          0        206         72 |
278
                    |      0.00       0.00      74.10      25.90 |
100.00
```

```
                   |      0.00       0.00      27.58      34.29 |
17.13
-------------------+--------------------------------------------+--------
--
      Iron Sheets |       203        394        534        135 |
1,266
                   |     16.03      31.12      42.18      10.66 |
100.00
                   |     80.24      95.40      71.49      64.29 |
78.00
-------------------+--------------------------------------------+--------
--
  Tiles/Asbestors |        50         19          7          3 |
79
                   |     63.29      24.05       8.86       3.80 |
100.00
                   |     19.76       4.60       0.94       1.43 |
4.87
-------------------+--------------------------------------------+--------
--
            Total |       253        413        747        210 |
1,623
                   |     15.59      25.45      46.03      12.94 |
100.00
                   |    100.00     100.00     100.00     100.00 |
100.00

          Pearson chi2(6) = 367.2853   Pr = 0.000

. tab     v153 source, row column chi2

+-------------------+
| Key               |
|-------------------|
|     frequency     |
|  row percentage   |
| column percentage |
+-------------------+

                   |                  source
     has telephone | Piped in   Yard Taps  Improved   Uniproved |
Total
-------------------+--------------------------------------------+--------
--
               no |       200        403        744        209 |
1,556
                   |     12.85      25.90      47.81      13.43 |
100.00
                   |     79.05      97.58      99.73      99.52 |
95.93
-------------------+--------------------------------------------+--------
--
              yes |        53         10          2          1 |
66
                   |     80.30      15.15       3.03       1.52 |
100.00
```

```
                    |     20.95       2.42       0.27       0.48 |
4.07
--------------------+--------------------------------------------+--------
--
              Total |       253        413        746        210 |
1,622
                    |     15.60      25.46      45.99      12.95 |
100.00
                    |    100.00     100.00     100.00     100.00 |
100.00

          Pearson chi2(3) = 222.0954   Pr = 0.000

.
. *****Model Building***********
. xi: mlogit source i.v101 i.v102 i.new_v136 i.v151 i.new_v152 i.v119
i.new_v11
> 6 i.new_v127 i.new_v128 i.new_v129, baseoutcome(4) nolog
i.v101            _Iv101_3-4          (naturally coded; _Iv101_3 omitted)
i.v102            _Iv102_1-2          (naturally coded; _Iv102_1 omitted)
i.new_v136        _Inew_v136_1-3      (naturally coded; _Inew_v136_1
omitted)
i.v151            _Iv151_1-2          (naturally coded; _Iv151_1 omitted)
i.new_v152        _Inew_v152_1-4      (naturally coded; _Inew_v152_1
omitted)
i.v119            _Iv119_0-1          (naturally coded; _Iv119_0 omitted)
i.new_v116        _Inew_v116_1-4      (naturally coded; _Inew_v116_1
omitted)
i.new_v127        _Inew_v127_1-3      (naturally coded; _Inew_v127_1
omitted)
i.new_v128        _Inew_v128_1-3      (naturally coded; _Inew_v128_1
omitted)
i.new_v129        _Inew_v129_1-3      (naturally coded; _Inew_v129_1
omitted)

Multinomial logistic regression                   Number of obs   =
1612
                                                  LR chi2(54)     =
1561.41
                                                  Prob > chi2     =
0.0000
Log likelihood = -1249.8087                       Pseudo R2       =
0.3845

--------------------------------------------------------------------------
---
-
      source |      Coef.   Std. Err.      z    P>|z|     [95% Conf.
Interval]
-------------+------------------------------------------------------------
---
-
Piped_in_h~e |
    _Iv101_4 |  -.4287103   .6574823    -0.65   0.514    -1.717352
.8599313
    _Iv102_2 |  -17.74811    1009.61    -0.02   0.986    -1996.548
1961.052
```

```
_Inew_v136_2 |   .1826392   .3053453     0.60   0.550    -.4158265
.7811049
_Inew_v136_3 |   .8459406   .4812238     1.76   0.079    -.0972407
1.789122
    _Iv151_2 |  -.3724731   .2715823    -1.37   0.170    -.9047646
.1598185
_Inew_v152_2 |   .5623106   .3522071     1.60   0.110    -.1280026
1.252624
_Inew_v152_3 |   .1288992   .4159942     0.31   0.757    -.6864346
.9442329
_Inew_v152_4 |   .1564069   .4219191     0.37   0.711    -.6705394
.9833532
    _Iv119_1 |   1.301799   .3545712     3.67   0.000      .606852
1.996745
_Inew_v116_2 |   -2.36651   .6886669    -3.44   0.001    -3.716273   -
1.016748
_Inew_v116_3 |  -1.904039   .7603693    -2.50   0.012    -3.394335   -
.4137424
_Inew_v116_4 |   -3.00915   3526.547    -0.00   0.999    -6914.915
6908.897
_Inew_v127_2 |   1.358199   .8268913     1.64   0.100    -.2624781
2.978876
_Inew_v127_3 |     .68179   .5425218     1.26   0.209    -.3815332
1.745113
_Inew_v128_2 |   .5260224   .3524921     1.49   0.136    -.1648493
1.216894
_Inew_v128_3 |   2.548052   1.376333     1.85   0.064    -.1495117
5.245615
_Inew_v129_2 |  -.2227021   1812.473    -0.00   1.000    -3552.605
3552.159
_Inew_v129_3 |  -.1316289   1812.473    -0.00   1.000    -3552.514
3552.251
       _cons |   1.236905   1812.473     0.00   0.999    -3551.145
3553.619
-------------+----------------------------------------------------------------
---
-
Yard_Taps_~s |
    _Iv101_4 |   .2913866   .5398272     0.54   0.589    -.7666553
1.349429
    _Iv102_2 |  -3.322761   .6105873    -5.44   0.000     -4.51949   -
2.126032
_Inew_v136_2 |   .0594373   .2531993     0.23   0.814    -.4368243
.5556989
_Inew_v136_3 |   .7666533   .3980065     1.93   0.054    -.0134252
1.546732
    _Iv151_2 |  -.0263675   .2268785    -0.12   0.907    -.4710412
.4183063
_Inew_v152_2 |    .574393   .2856113     2.01   0.044     .0146052
1.134181
_Inew_v152_3 |  -.1492571   .3365727    -0.44   0.657    -.8089275
.5104134
_Inew_v152_4 |  -.5239557   .3532442    -1.48   0.138    -1.216302
.1683902
    _Iv119_1 |   .3962951   .3030993     1.31   0.191    -.1977686
.9903588
_Inew_v116_2 |   .2393612   .7096346     0.34   0.736    -1.151497
```

```
1.630219
_Inew_v116_3 |   .2871073   .7744649     0.37   0.711    -1.230816
1.805031
_Inew_v116_4 |  -14.89106    2070.54    -0.01   0.994    -4073.075
4043.293
_Inew_v127_2 |  -.6408452   .7674541    -0.84   0.404    -2.145028
.8633372
_Inew_v127_3 |   .7044803   .3269072     2.15   0.031      .063754
1.345207
_Inew_v128_2 |  -.0575139   .2670829    -0.22   0.830    -.5809867
.4659588
_Inew_v128_3 |   1.419019   1.284027     1.11   0.269    -1.097628
3.935665
_Inew_v129_2 |   16.29562   1119.537     0.01   0.988    -2177.956
2210.547
_Inew_v129_3 |   16.44838   1119.537     0.01   0.988    -2177.803
2210.7
       _cons |   -15.5558   1119.537    -0.01   0.989    -2209.808
2178.696
-------------+------------------------------------------------------------
---
-
Improved_S~s |
    _Iv101_4 |  -.3437764    .622419    -0.55   0.581    -1.563695
.8761425
    _Iv102_2 |   1.600127   .6183285     2.59   0.010     .3882255
2.812029
_Inew_v136_2 |  -.0710765   .2054496    -0.35   0.729    -.4737504
.3315973
_Inew_v136_3 |  -.2072225   .2842835    -0.73   0.466    -.7644079
.349963
    _Iv151_2 |   .3994719   .1958299     2.04   0.041     .0156522
.7832915
_Inew_v152_2 |   .2846955   .2394723     1.19   0.235    -.1846616
.7540526
_Inew_v152_3 |   .3551538    .260621     1.36   0.173    -.1556539
.8659616
_Inew_v152_4 |  -.2018116   .2674268    -0.75   0.450    -.7259585
.3223352
    _Iv119_1 |  -.0281467   .3285618    -0.09   0.932     -.672116
.6158225
_Inew_v116_2 |   1.162473   .9849343     1.18   0.238    -.7679626
3.092909
_Inew_v116_3 |   1.671043   1.033694     1.62   0.106    -.3549591
3.697046
_Inew_v116_4 |   .4170078   1.028155     0.41   0.685     -1.59814
2.432155
_Inew_v127_2 |  -1.539433   .7077543    -2.18   0.030    -2.926606     -
.15226
_Inew_v127_3 |   .4669416   .2606049     1.79   0.073    -.0438347
.9777178
_Inew_v128_2 |  -.3417192   .2243759    -1.52   0.128    -.7814879
.0980495
_Inew_v128_3 |  -.1457687   1.184257    -0.12   0.902     -2.46687
2.175332
_Inew_v129_2 |   .6286571   .2360294     2.66   0.008     .1660479
1.091266
```

```
_Inew_v129_3 |   .8912379   .7980131     1.12   0.264     -.672839
2.455315
       _cons |  -1.380163   1.049088    -1.32   0.188    -3.436338
.6760117
-------------+----------------------------------------------------------
---
-
Uniproved_~s |  (base outcome)
------------------------------------------------------------------------
---
-

.
. log close
      name:  <unnamed>
       log:  C:\Users\Circuit City\Documents\PERSONAL
DOCUMENTS\udhs2007\Plan
o
> f Analysis 22 June 2012.smcl
  log type:  smcl
 closed on:  23 Jun 2012, 21:38:32
------------------------------------------------------------------------
---
--
```

Appendix- C: Design for UWDS transitions

C-1: Pipe and Nodal data for existing hypothetical UWDS

			PIPES				**JUNCTIONS**	
ID	Node1	Node2	Length	Diameter	Roughness	ID	Elev	Demand
2	T1	1	1000	355.6	105	8	8	5
3	1	2	1000	152.4	105	1	12	5
4	2	3	1000	152.4	105	2	8	5
5	4	5	1000	203.2	105	3	4	5
7	2	5	1000	50	105	4	4	5
8	5	8	1000	152.4	105	5	8	5
9	8	6	1500	90	105	6	10	5
10	6	3	1000	152.4	105	7	8	5
12	1	4	1000	254	105			
13	4	7	1000	100	105			

C-2: Pipe and Nodal data for hypothetical UWDS$_1$

			[PIPES]				[JUNCTIONS]	
;ID	Node1	Node2	Length	Diameter	Roughness	;ID	Elev	Demand
2	T1	1	1000	457.2	100	8	8	10
3	1	2	1000	304.8	100	1	12	10
4	2	3	1000	304.8	100	2	8	10
5	4	5	1000	254	100	3	4	10
7	2	5	1000	40	100	4	4	10
8	5	8	1000	304.8	100	5	8	10
9	8	6	1500	125	100	6	10	10
10	6	3	1000	125	100	7	8	10
12	1	4	1000	457.2	100	10	6	10
13	4	7	1000	304.8	100	9	2	10
14	10	7	1000	125	130	0	Open	;
15	7	8	1000	152.4	130	0	Open	;
20	3	9	1000	125	130	0	Open	;

C-3: Pipe and Nodal data for hypothetical UWDS$_2$

[PIPES]						[JUNCTIONS]		
;ID	Node1	Node2	Length	Diameter	Roughness	;ID	Elev	Demand
2	T1	1	1000	457.2	95	8	8	15
3	1	2	1000	304.8	95	1	12	15
4	2	3	1000	304.8	95	2	8	15
5	4	5	1000	254	95	3	4	15
7	2	5	1000	40	95	4	4	15
8	5	8	1000	304.8	95	5	8	15
9	8	6	1500	125	95	6	10	15
10	6	3	1000	254	95	7	8	15
12	1	4	1000	457.2	95	10	6	15
13	4	7	1000	304.8	95	11	10	15
14	10	7	1000	125	120	12	10	15
15	7	8	1000	152.4	120	9	2	15
16	8	11	1000	254	130	0	Open	;
17	11	12	1000	152.4	130	0	Open	;
18	12	6	2000	203.2	130	0	Open	;
20	3	9	1000	125	120	0	Open	;

C-4: Pipe and Nodal data for hypothetical UWDS$_3$

[PIPES]						*[JUNCTIONS]*		
;ID	Node1	Node2	Length	Diameter	Roughness	;ID	Elev	Demand
2	T1	1	1000	609	90	8	8	20
3	1	2	1000	355.6	90	1	12	20
4	2	3	1000	406.4	90	2	8	20
5	4	5	1000	406.4	90	3	4	20
7	2	5	1000	40	90	4	4	20
8	5	8	1000	457.2	90	5	8	20
9	8	6	1500	40	90	6	10	20
10	6	3	1000	304.8	90	7	8	20
12	1	4	1000	508	90	10	6	20
13	4	7	1000	254	90	11	10	20
14	10	7	1000	203.2	120	12	10	20
15	7	8	1000	40	120	9	2	20
16	8	11	1000	355.6	125	14	8	20
17	11	12	1000	254	125	15	4	20
18	12	6	2000	50	125	13	12	20
20	3	9	1000	152.4	120	0	Open	;
25	14	15	1000	203.2	130	0	Open	;
26	14	2	1000	40	130	0	Open	;

27	15	3	1000	50	130	0	Open	;
28	1	13	1000	254	130	0	Open	;
29	13	14	1000	304.8	130			

Appendix- D: Iganga Case Study

D-1: Pipe and Nodal data for original I-UWDS$_0$

[PIPES] ;ID	Node1	Node2	Length	Diameter	Roughness	[JUNCTIONS] ;ID	Elev	Demand
26	151	17	125	70	100	17	1170.15	0.23
77	436	411	55	60	100	147	1172.645	0.23
92	291	147	235	70	100	151	1168.763	0.23
181	182GL	181	10	110	100	181	1174.648	0
207	272	262	262.5	40	100	231	1166.13	0.477
212	271	151	175	70	100	261	1167.979	0.24
217	262	271	9.88	90	100	262	1170.182	0.23
222	391	336	205	60	100	271	1170.358	0
231	261	231	330	40	100	272	1168.771	0.23
232	376	391	40	50	100	291	1171.115	0.23
261	262	261	174.22	80	100	292	1167.783	0.23
266	336	261	205	80	100	322	1162.901	0.24
291	292	291	225	70	100	336	1169.048	0.24
391	392	391	150	70	100	376	1166.896	0.23
396	396	376	430	41	100	381	1161.672	0.23
406	322	392	235	70	100	391	1166.939	0.24
411	411	322	70	60	100	392	1165.084	0.24
436	438	436	240	40	100	396	1160.941	0.23
437	437	438	190	40	100	411	1161.658	1.34
442	437	396	115	40	100	436	1160.461	0.67
467	381	292	225	70	100	437	1158.431	0.23
522	147	181	255	100	100	438	1158.212	0.67
link1	147	17	100	80	100	182GL	1176.326	0
457a	381	add1	80	70	100	add1	1163.26	0
376a	272	1	185	50	100	1	1164.5	0
376b	1	376	130	70	100			
link2	add1	1	65	90	100			
1	2	182GL	10	100	100			

D-2: Pipe and Nodal data for I- UWDS$_1$ [Scenario 1]

			[PIPES]				[JUNCTIONS]	
;ID	Node1	Node2	Length	Diameter	Roughness	;ID	Elev	Demand
26	151	17	125	100	110	17	1170.15	0.38
77	436	411	55	40	110	147	1172.65	0.38
92	291	147	235	50	110	151	1168.76	0.38

171	301	171	280	80	110	171	1174.55	0.8
181	182GL	181	10	152.4	110	181	1174.65	0
207	272	262	262.5	40	110	231	1166.13	0.39
212	271	151	175	125	110	261	1167.98	0.39
217	262	271	9.88	152.4	110	262	1170.18	0.39
222	391	336	205	100	110	271	1170.36	0
231	261	231	330	40	110	272	1168.77	0.38
232	376	391	40	100	110	291	1171.12	0.38
261	262	261	174.22	110	110	292	1167.78	0.38
266	336	261	205	110	110	301	1170.98	0.8
291	292	291	225	50	110	302	1165.82	0.84
301	302	301	395	70	110	322	1162.9	0.39
391	392	391	150	60	110	336	1169.05	0.39
396	396	376	430	80	110	376	1166.9	0.38
406	322	392	235	60	110	381	1161.67	0.38
411	411	322	70	40	110	391	1166.94	0.39
436	438	436	240	80	110	392	1165.08	0.39
437	437	438	190	70	110	396	1160.94	0.38
442	437	396	115	70	110	401	1160	0.8
467	381	292	225	40	110	411	1161.66	1.1
472	302	292	305	40	110	421	1159.54	0.8
522	147	181	255	152.4	110	436	1160.46	1.1
537	181	171	55	70	110	437	1158.43	0.38
link1	147	17	100	125	110	438	1158.21	1.1
457a	381	add1	80	40	110	182GL	1176.33	0
376a	272	1	185	50	110	add1	1163.26	0
376b	1	376	130	40	110	1	1164.5	0.23
link2	add1	1	65	40	110			
2	421	381	105	40	110			
3	401	302	155	50	110			
8	421	401	230	50	110			
1	2	182GL	10	125	110			

D-3: Pipe and Nodal data for I- UWDS$_2$ [Scenario 2]

			[PIPES]				[JUNCTIONS]	
;ID	Node1	Node2	Length	Diameter	Roughness	;ID	Elev	Demand
26	151	17	125	152.4	120	17	1170.15	0.61
77	436	411	55	70	120	98	1171.644	0.61
82	436	366	65	60	120	116	1173.007	0.61
87	147	116	280	50	120	147	1172.645	0.61
92	291	147	235	125	120	151	1168.763	0.61
102	116	98	140	40	120	171	1174.553	1.3

171	301	171	280	80	120	181	1174.648	0
181	182GL	181	10	203.2	120	231	1166.13	0.63
207	272	262	262.5	40	120	261	1167.979	0.63
212	271	151	175	152.4	120	262	1170.182	0.61
217	262	271	9.88	152.4	120	271	1170.358	0
222	391	336	205	152.4	120	272	1168.771	0.61
227	346	336	90	70	120	291	1171.115	0.61
231	261	231	330	40	120	292	1167.783	0.61
232	376	391	40	80	120	297	1169.498	0.63
261	262	261	174.22	125	120	301	1170.978	1.3
266	336	261	205	152.4	120	302	1165.821	1.3
291	292	291	225	125	120	322	1162.901	0.63
301	302	301	395	70	120	336	1169.048	0.63
326	346	297	220	50	120	346	1169.153	0.63
351	351	346	150	40	120	351	1167.106	0.63
391	392	391	150	125	120	361	1167.341	1.3
396	396	376	430	60	120	366	1160.042	1.78
406	322	392	235	80	120	376	1166.896	0.61
411	411	322	70	70	120	381	1161.672	0.61
431	432	416	305	70	120	391	1166.939	0.63
436	438	436	240	40	120	392	1165.084	0.63
437	437	438	190	70	120	396	1160.941	0.61
442	437	396	115	50	120	401	1160.001	1.3
447	456	437	65	70	120	411	1161.658	1.78
452	456	432	175	80	120	416	1162.678	0.61
456	457	456	440	40	120	421	1159.544	1.3
467	381	292	225	80	120	432	1160.377	0.61
472	302	292	305	80	120	436	1160.461	1.78
492	302	361	430	50	120	437	1158.431	0.61
522	147	181	255	203.2	120	438	1158.212	1.78
537	181	171	55	125	120	456	1157.781	0.61
link1	147	17	100	152.4	120	457	1150.194	0.67
457a	381	add1	80	60	120	182GL	1176.326	0
457b	add1	416	80	80	120	add1	1163.26	0
376a	272	1	185	40	120	1	1164.5	0.31
376b	1	376	130	50	120			
link2	add1	1	65	60	120			
2	421	381	105	60	120			
3	401	302	155	50	120			
8	421	401	230	40	120			
1	2	182GL	10	254	120			

D-4: Pipe and Nodal data for I- UWDS$_3$ [Scenario 3]

[PIPES]						[JUNCTIONS]		
;ID	Node1	Node2	Length	Diameter	Roughness	;ID	Elev	Demand
26	151	17	125	254	130	17	1170.15	1
72	411	371	320	60	130	98	1171.644	1
77	436	411	55	80	130	116	1173.007	1
82	436	366	65	80	130	147	1172.645	1
87	147	116	280	60	130	151	1168.763	1
92	291	147	235	60	130	171	1174.553	2.12
102	116	98	140	50	130	181	1174.648	0
142	371	276	245	60	130	222	1168.887	1.04
147	276	226	225	90	130	226	1165.952	5.08
152	231	226	125	100	130	231	1166.13	1.04
157	286	231	100	100	130	261	1167.979	1.04
162	321	286	90	80	130	262	1170.182	1
167	222	321	225	60	130	271	1170.358	0
171	301	171	280	110	130	272	1168.771	1
181	182GL	181	10	304.8	130	276	1163.296	5.08
207	272	262	262.5	50	130	286	1167.265	1.04
212	271	151	175	254	130	291	1171.115	1
217	262	271	9.88	203	130	292	1167.783	1
222	391	336	205	152.4	130	297	1169.498	1.04
227	346	336	90	90	130	301	1170.978	2.12
231	261	231	330	152.4	130	302	1165.821	1.04
232	376	391	40	110	130	311	1169.132	1.04
237	322	356	300	90	130	321	1167.192	1.04
247	356	321	85	100	130	322	1162.901	1.04
261	262	261	174.22	254	130	336	1169.048	1.04
266	336	261	205	203.2	130	341	1168.325	1.04
291	292	291	225	50	130	346	1169.153	1.04
301	302	301	395	125	130	351	1167.106	1.04
311	222	311	85	90	130	356	1166.745	1.04
326	346	297	220	80	130	361	1167.341	2.12
336	336	222	75	100	130	366	1160.042	2.91
341	341	222	90	60	130	371	1162.11	2.91
351	351	346	150	70	130	376	1166.896	1
356	341	356	215	60	130	381	1161.672	1
391	392	391	150	90	130	391	1166.939	1.04
396	396	376	430	70	130	392	1165.084	1.04
406	322	392	235	110	130	396	1160.941	1
411	411	322	70	110	130	401	1160.001	2.12
431	432	416	305	50	130	411	1161.658	2.91

436	438	436	240	70	130	416	1162.678	1
437	437	438	190	50	130	421	1159.544	2.12
442	437	396	115	50	130	432	1160.377	1
447	456	437	65	60	130	436	1160.461	2.91
452	456	432	175	50	130	437	1158.431	1
456	457	456	440	60	130	438	1158.212	2.91
467	381	292	225	40	130	456	1157.781	1
472	302	292	305	40	130	457	1150.194	1.09
492	302	361	430	60	130	182GL	1176.326	0
522	147	181	255	254.2	130	add1	1163.26	0
537	181	171	55	152.4	130	1	1164.5	0.5
link1	147	17	100	203.2	130			
457a	381	add1	80	70	130			
457b	add1	416	80	80	130			
376a	272	1	185	40	130			
376b	1	376	130	80	130			
link2	add1	1	65	90	130			
2	421	381	105	50	100			
3	401	302	155	90	100			
8	421	401	230	50	100			
1	2	182GL	10	304.8	100			

D-5: Results for sensitivity analysis of PTIC to unit cost of leakage [Platform]

	Phase-1			Phase-2			Phase-3		
	BIC	LIC	TIC	BIC	LIC	TIC	BIC	LIC	TIC
0%	109639	132960	724489	91565.3	131367	1.07E+06	83782.4	137651	1.72E+06
10%	120603	132960	726059	109917	131368	9.33E+05	92160.7	137651	1.76E+06
20%	131567	132960	621279	119909	131368	1.11E+06	100539	137651	1.60E+06
50%	164458	132960	838278	149886	131368	1.07E+06	125674	137651	1.83E+06
100%	219278	132960	715361	199848	131368	1.25E+06	167565	137651	1.79E+06

D-6: Results for sensitivity analysis of PTIC to unit cost of burst repair costs

	Phase-1			Phase-2			Phase-3		
	BIC	LIC	TIC	BIC	LIC	TIC	BIC	LIC	TIC
0%	109639	132960	724489	91565.3	131367	1.07E+06	83782.4	137651	1.72E+06
10%	109639	146256	646600	99924.2	99924.2	1.45E+05	83782.4	151416	1.55E+06
20%	109639	159552	743145	99924.2	157642	1.17E+06	83782.4	165181	1.71E+06
50%	109639	199440	711981	99924.2	197052	9.32E+05	83782.4	206476	1.66E+06
100%	109639	265920	647023	99924.2	262737	1.07E+06	83782.4	275301	1.70E+06

D-7: Results for sensitivity analysis of PTIC to unit cost of leakage [Non platform]

% LIC Change	Phase-1			Phase-2			Phase-3		
	BIC	LIC	TIC	BIC	LIC	TIC	BIC	LIC	TIC
0%	109639	132960	724489	91565.3	131367	1.07E+06	83782.4	137651	1.72E+06
10%	109639	146256	646600	99924.2	99924.2	1.45E+05	83782.4	151416	1.55E+06
20%	109639	159552	743145	99924.2	157642	1.17E+06	83782.4	165181	1.71E+06
50%	109639	199440	711981	99924.2	197052	9.32E+05	83782.4	206476	1.66E+06
100%	109639	265920	647023	99924.2	262737	1.07E+06	83782.4	275301	1.70E+06

D-8: Results for sensitivity analysis of PTIC to unit cost of burst repair costs

% BIC Change	Phase-1			Phase-2			Phase-3		
	BIC	LIC	TIC	BIC	LIC	TIC	BIC	LIC	TIC
0%	184120	308970	416306 9	91565.3	131367	1.07E+06	83782.4	137651	1.72E+06
10%	202532	308970	390963	99924.2	99924.2	1.45E+05	83782.4	151416	1.55E+06
20%	220945	308970	361945	99924.2	157642	1.17E+06	83782.4	165181	1.71E+06
50%	276181	308970	431276	99924.2	197052	9.32E+05	83782.4	206476	1.66E+06
100%	368241	308970	309745	99924.2	262737	1.07E+06	83782.4	275301	1.70E+06

D-9: Variation of TIC BIC and OIC for the different I-UWDS transition platforms

Platform	*Scenario-1*			*Scenario-2*			*Scenario-3*		
	BIC	LIC	TIC	BIC	LIC	TIC	BIC	LIC	TIC
PF-1[7]	1397.55	2.4984	1.03E+06	3432.6	34305.6	1.52E+06	2246.3	8108.07	2.41E+06
PF-2[7-26]	3277.47	5788.5	1.08E+06	14071.7	77206.1	1.44E+06	4287.84	8110.17	2.18E+06
PF-3[7-26-3]	32298	22324.1	915793	14071.7	77206.1	1.55E+06	9350.07	13202	1.92E+06
PF-4[7-26-3-17]	37657.2	66861.5	945738	15341.7	77208.3	1.34E+06	9764.92	13203.3	1.97E+06
PF-5[7-26-3-14]	69904.5	81525.6	751449	67429.2	94266.8	1.35E+06	32732.5	60076.8	1.94E+06
PF-6[7-26-3-14-25]	75189.5	81528.6	800681	70481.8	101121	1.14E+06	11129.5	13204.7	1.91E+06
PF-7[7-26-3-14-25-23]	81352.5	92208.2	782440	80347.7	131364	1.31E+06	39260.1	89102.9	1.71E+06
PF-8[7-26-3-14-25-23-8]	81405.6	92208.3	765997	80380.8	131364	1.36E+06	42480.5	102937	1.73E+06
PF-9[7-26-3-14-25-23-8-16]	99080.2	106274	690945	91565.3	131367	1.20E+06	76606.9	128299	1.77E+06
PF-10[7-26-3-14-25-23-8-16-12]	109639	132960	724489	91565.3	131367	1.07E+06	83782.4	137651	1.72E+06

D-10: Comparison between PTIC, TIC, BIC and OIC for the different I-UWDS

Transition without UWDS Transition Platform			*UWDS Transition Platform Based on PTIC*		
Phase 1	Phase 2	Phase 3	Phase 1	Phase 2	Phase 3
184,120	110,685	36,790	109,639	91,565	83,782
308,970	160,883	98,064	132,960	131,367	137,651
416,307	1,164,050	1,926,490	724,489	1,068,200	1,720,530
909,397	1,435,618	2,061,344	967,088	1,291,132	1,941,963
	4,406,359			4,200,184	

Appendix- E: Rubaga Case Study

E-1: RWDN Transition lifecycle costs for the two approaches

Pipe Index	Original UWDS	Conventional approach Based on an Exixting System				SIC-SC1		Conventional approach Transition without UWDS Transition Platform				UWDS Transition Platform Based on PTIC			
		Diameter		PTIC		SC1	SC2	Diameter		PTIC		Diameter		PTIC	
		SC1	SC2	SC1	SC2			SC1	SC2	SC1	SC2	SC1	SC2	SC1	SC2
1	40	40	40	-	-	1.8	2.0	152.4	203	69,337	265,133	152	203	146,013	262,265
2	40	40	40	-	-	1.4	1.4	-	-	67,064	261,949	70	90	325,851	112,316
3	70	70	70	-	-	1.7	1.7	-	-	55,461	280,771	40	60	44,480	127,608
4	100	100	100	-	-	1.7	1.7	-	-	49,820	355,854	80	70	33,314	92,258
5	40	40	40	-	-	1.7	1.7	-	50	51,693	108,375	203	40	31,400	15,392
6	40	40	40	-	-	1.7	1.7	-	-	55,813	52,497	-	-	23,872	53,103
7	60	60	60	-	-	1.7	1.7	-	-	48,098	42,400	-	-	16,156	43,006
8	125	125	125	-	-	1.7	1.7	-	-	50,173	24,513	-	-	18,231	25,119
9	40	40	40	-	-	1.4	1.4	-	40	47,619	28,972	-	40	15,677	28,972
10	80	80	80	-	-	1.8	1.8	-	-	63,056	33,655	100	50	11,193	32,608
11	40	40	40	-	-	2.0	1.9	50	-	61,666	26,914	305	100	48,114	26,894
12	70	70	70	-	-	1.9	1.9	-	40	44,784	29,119	-	40	46,669	30,630
13	40	40	40	-	-	1.4	1.4	-	-	45,669	31,314	125	40	2,670	46,620
14	80	80	80	-	-	1.9	1.9	-	-	60,756	18,112	-	-	18,642	29,817
15	125	125	125	-	-	1.9	2.0	110	305	41,197	104,804	152	254	122,864	182,244
16	80	80	80	-	-	2.0	1.9	406.4	100	121,432	10,913	254	50	39,216	10,578
17	80	80	80	-	-	1.7	1.6	508	70	260,784	23,023	762	40	108,219	23,023
18	40	40	40	-	-	1.7	1.7	-	-	246,825	34,933	-	40	94,261	29,180
19	152	152	152	-	-	1.6	1.6	-	-	249,273	26,521	-	-	96,708	32,679
20	50	50	50	-	-	1.9	1.9	508	125	104,598	19,477	254	356	25,382	16,359
21	254	254	254	-	-	1.9	1.8	-	-	132,066	67,118	110	356	104,133	340,067
22	40	40	40	-	-	1.5	1.4	355.6	50	285,530	64,879	609	203	162,446	64,132
23	40	40	40	-	-	1.5	1.4	-	-	308,835	13,573	-	40	213,219	13,184
24	60	60	60	-	-	2.1	1.9	70	40	197,085	5,032	356	152	187,222	9,425
25	40	40	40	-	-	1.9	1.9	-	50	153,861	5,374	110	40	65,421	9,131
26	254	254	254	-	-	2.0	1.9	-	40	153,260	11,829	-	-	21,597	2,310
27	70	70	70	-	-	1.6	1.7	-	40	149,705	87,661	305	110	159,290	90,071
28	90	90	90	-	-	1.4	1.4	-	-	165,189	88,096	-	-	171,219	93,662
29	60	60	60	-	-	1.7	1.6	-	-	163,221	127,758	305	457	191,843	23,879
30	40	40	40	-	-	1.8	1.8	40	40	33,123	60,883	70	609	149,519	73,478
31	70	70	70	-	-	2.0	1.9	-	-	19,775	41,644	203	40	51,389	105,055
32	40	40	40	-	-	1.9	1.9	-	50	64,794	66,075	-	-	81,091	217,008
33	40	40	40	-	-	1.9	1.9	-	-	13,623	42,002	-	-	29,920	101,405
34	40	40	40	-	-	1.4	1.4	-	-	26,835	45,999	457	40	36,291	10,040
35	40	40	40	-	-	1.7	1.7	355.6	50	72,786	20,395	762	152	59,575	16,046
36	60	60	60	-	-	1.4	1.4	-	-	57,002	16,604	762	125	114,869	20,657
37	100	100	100	-	-	1.4	1.4	-	40	74,446	18,249	-	-	129,741	44,568
38	40	40	40	-	-	1.8	1.8	-	-	79,338	42,278	-	40	134,632	37,851
39	60	60	60	-	-	1.9	1.8	254	60	114,704	98,056	100	508	72,125	93,167
40	110	110	110	-	-	1.9	2.2	110	457	37,561	552,468	100	356	45,175	471,117
41	60	60	60	-	-	1.8	1.8	-	-	14,978	614,340	457	110	24,538	66,020
42	100	100	100	-	-	1.4	1.4	-	-	15,047	528,212	356	152	29,725	32,066
43	40	40	40	-	-	1.4	1.4	-	-	15,080	533,542	-	-	7,243	13,464
44	40	40	40	-	-	2.0	1.9	457.2	40	497,715	121,488	356	356	282,245	121,488
45	110	110	110	-	-	1.4	1.4	-	-	505,441	119,766	50	100	8,090	66,194

46	70	70	70	-	-	2.0	2.0	609	254	316,401	26,960	80	90	206,486	23,804
47	60	60	60	-	-	1.8	1.8	-	305	317,872	49,067	100	50	53,436	19,498
48	40	40	40	-	-	1.7	1.7	-	254	316,263	100,007	356	254	41,017	48,175
49				*	*	1.6	1.7	90	80	13,478	96,859	406	110	5,511	269,690
50				*	*	1.8	1.9	406.4	50	20,307	81,275	40	152	8,552	507,241
51				*	*	1.8	2.2	609	110	290,166	231,479	305	125	35,688	1,492,280
52				*	*	2.0	1.9	762	305	556,190	194,807	305	508	151,916	152,659
53				*	*	1.8	1.9	40	305	121,555	361,838	305	356	133,986	637,140
54				*	*	4.7	1.8	406.4	100	4,347,890	17,113	356	457	2,900,000	48,979
55				*	*	1.4	1.4	60	40	59,612	16,533	70	762	564,802	46,801
56				*	*	2.8	2.0	152.4	457	518,832	135,001	305	356	2,400,000	28,548
57				*	*	1.9	2.1	40	406	22,494	254,364	609	609	19,297	350,981
58				*	*	2.0	1.9	254	80	135,157	9,080	254	40	205,180	14,786
59				*	*	1.9	2.0	50	152	15,169	68,565	90	254	9,591	57,600
60				*	*	2.1	2.1	60	203	68,739	36,773	80	457	58,633	86,564
61				*	*	2.0	2.1	80	457	59,794	147,905	70	80	59,793	41,195
62				*	*	1.9	1.9	60	609	7,930	165,841	203	60	1,995	66,853
63				*	*	1.9	2.2	152.4	305	36,414	122,196	762	762	97,939	214,482
64				*	*	2.0	2.0	508	50	401,226	28,151	110	100	285,596	30,929
65				*	*	2.0	2.0	50	152	57,049	36,895	305	125	192,223	118,711
66				*	*	2.0	2.0	203.2	356	79,531	154,120	457	203	40,463	54,393
67				*	*	2.0	1.9	609	40	275,557	15,186	305	110	34,891	16,908
68				*	*	1.9	1.9	152.4	40	15,791	5,353	305	90	7,190	7,247
69				*	*	2.0	2.0	406.4	305	193,342	31,771	762	609	50,349	79,595
70				*	*	1.8	1.8	609	40	160,197	14,478	70	80	25,455	26,591
71				*	*	1.8	1.9	508	50	131,709	90,828	70	100	60,358	101,929
72				*	*	1.9	1.9	40	40	19,588	12,220	70	40	138,014	105,169
73				*	*	1.9	2.0	50	609	51,744	316,329	100	100	50,788	96,710
74				*	*	1.7	1.7	110	40	15,325	45,143	762	40	6,378	59,189
75				*	*	1.9	1.9	50	70	16,328	41,665	50	40	27,219	54,043
76				*	*	1.7	1.7	254	80	26,552	13,890	125	305	9,492	14,614
77				*	*	1.9	1.9	40	508	32,940	40,279	125	762	25,352	69,702
78				*	*	1.8	1.7	152.4	80	53,952	6,499	609	80	42,750	17,566
79				*	*	2.0	2.0	125	508	96,769	243,537	60	90	379,231	76,391
80				*	*	1.9	2.0	762	762	139,251	557,306	125	457	15,193	195,320
81				*	*	2.0	2.2	762	508	281,725	887,908	110	152	274,137	434,974
82				*	*	1.7	1.7	304.8	110	65,131	3,610	110	457	23,316	5,332
83				*	*	1.7	1.7	254	40	51,604	3,609	508	406	85,195	5,333
84				*	*	2.0	5.4	609	356	519,691	4,138,260	457	609	512,102	4,139,980
85				*	*		1.7		50		102,057		90		103,780
86				*	*		1.6		40		35,270		50		83,614
87				*	*		1.6		50		38,313		40		41,528
88				*	*		1.6		203		60,793		125		35,208

89	*	*	1.6	40	47,504	508	49,226
90	*	*	1.6	406	85,174	40	117,763
91	*	*	1.8	356	358,183	356	179,680
92	*	*	1.7	508	577,345	762	120,842
93	*	*	1.7	110	31,058	508	26,500
94	*	*	2.2	203	274,710	406	450,059
95	*	*	2.0	609	576,831	356	578,553
96	*	*	2.7	457	2,001,380	356	2,336,710
97	*	*	1.4	40	38,383	356	40,869
98	*	*	1.8	609	118,659	40	18,928
99	*	*	1.8	762	546,227	70	121,055
100	*	*	2.0	609	66,072	508	14,903
101	*	*	2.3	356	248,554	406	66,906
102	*	*	2.2	40	55,785	90	62,667
103	*	*	1.8	90	3,851	70	5,537
104	*	*	1.8	254	50,104	60	51,826
105	*	*	1.9	356	224,128	40	474,391
106	*	*	2.0	40	51,978	80	58,484
107	*	*	2.0	100	49,261	356	250,304
108	*	*	2.0	110	44,172	254	40,738
109	*	*	1.9	40	9,348	508	28,160
110	*	*	2.0	609	329,747	254	52,769
111	*	*	1.9	40	22,921	70	168,744
112	*	*	2.0	100	28,760	609	45,304
113	*	*	1.7	100	16,747	762	16,709
114	*	*	1.8	508	265,770	100	56,804
115	*	*	1.9	40	10,356	305	12,078
116	*	*	2.0	60	13,025	40	22,610
117	*	*	2.0	40	12,386	80	33,493
118	*	*	1.6	50	25,864	406	34,287
119	*	*	2.1	762	446,412	305	59,055
120	*	*	2.1	762	796,574	609	224,806
121	*	*	1.9	356	49,823	50	28,055
122	*	*	2.0	152	37,078	356	119,336
123	*	*	2.0	508	143,556	60	26,521
124	*	*	1.9	203	43,342	125	33,903
125	*	*	1.9	152	82,123	457	652,456
Total UWDS transition costs				15,055,382	21,994,892	13,041,002	20,119,215
UWDS Life cycle transition impact cost				37,050,274		33,160,216	

* PTIC and optimal diameter could not be ascertained by model due to failure to meet minimum hydraulic constraints

- means that transition costs are also not considered because a pipe is retained during the UWDS transition process. Hence SC1-UWDS network for Scenario1-UWDS1; SC2-UWDS network for Scenario2-UWDS2.

E-2: Pipe SII data for RWDN

Sno	Pipe ID	SII	Year of Installation	Sno	Pipe ID	SII	Year of Installation	Sno	Pipe ID	SII	Year of Installation
1	P-3011	0.76	1998	61	P-9	0.91	1989	121	33	0.91	1999
2	P-3022	0.39	1998	62	P-10	0.91	1997	122	34	0.91	1989
3	P-805	0.68	1964	63	P-13	0.91	1991	123	35	0.91	1997
4	P-3060	0.64	1998	64	P-14	0.91	1998	124	36	0.91	1991
5	P-838	0.68	1998	65	P-15	0.91	1998	125	37	0.68	1994
6	P-2822	0.68	1964	66	P-16	0.91	1998				
7	P-839	0.68	1998	67	P-30	0.91	1998				
8	P-804	0.68	1997	68	P-31	0.91	1998				
9	P-3026	0.39	1998	69	P-32	0.91	1998				
10	P-3002	0.76	1998	70	P-35	0.76	1998				
11	P-2973	0.85	1998	71	P-37	0.76	1998				
12	P-809	0.85	1964	72	P-39	0.85	1998				
13	P-3012	0.39	1998	73	P-40	0.85	1998				
14	P-2819	0.85	1964	74	P-42	0.68	1998				
15	P-2820	0.85	1997	75	P-43	0.85	1998				
16	P-1711	0.91	1972	76	P-48	0.68	1998				
17	P-3081	0.57	1998	77	P-53	0.85	1998				
18	P-825	0.68	1998	78	P-54	0.68	1998				
19	P-3080	0.57	1998	79	P-4	0.85	1998				
20	P-3007	0.91	1998	80	P-6	0.85	1998				
21	P-2979	0.76	1972	81	P-8	0.85	1998				
22	P-3028	0.39	1987	82	P-48A	0.68	1998				
23	P-3024	0.39	1992	83	P-2830AA 0.68						
24	P-3034	0.91	1992	84	2	0.85	1998				
25	P-2809	0.91	1987	85	P-3088S	0.57	1998				
26	P-3005	0.91	1990	86	P-3082S	0.57	1998				
27	P-3057	0.57	2002	87	P-3075S	0.57	1998				
28	P-3021	0.39	1997	88	P-3140S	0.57	1998				
29	P-3074	0.57	1994	89	P-3065S	0.57	1998				
30	P-2999	0.76	1987	90	P-3056S	0.57	1998				
31	P-3009	0.91	1995	91	3	0.57	1998				
32	P-1720	0.76	1989	92	4	0.64	1998				
33	P-2803	0.91	1990	93	5	0.64	1998				
34	P-3020	0.39	1993	94	6	0.64	1998				
35	P-3059	0.64	1992	95	1	0.64	1998				
36	P-3092	0.39	1988	96	7	0.64	1998				
37	P-3093	0.39	1995	97	8	0.39	1998				
38	P-3095	0.76	1997	98	9	0.76	1998				
39	P-3097	0.76	1999	99	10	0.76	1998				

40	P-3098	0.91	1989	100	11	0.91	1998
41	P-3100	0.76	1997	101	13	0.91	1998
42	P-3101	0.39	1991	102	14	0.91	1998
43	P-3102	0.39	1987	103	P-3094	0.76	1998
44	P-3114	0.76	1992	104	15	0.76	1987
45	P-3120	0.39	1992	105	16	0.76	1992
46	P-3126	0.91	1987	106	17	0.91	1992
47	P-3132	0.76	1990	107	18	0.91	1987
48	P-2907	0.64	2002	108	19	0.91	1990
49	P-3147	0.64	1997	109	12	0.91	2002
50	P-2991	0.76	1994	110	20	0.85	1997
51	P-3146	0.76	1987	111	21	0.91	1994
52	P-811	0.85	1995	112	22	0.91	1987
53	P-2830A	0.68	1989	113	23	0.68	1995
54	P-3144	0.76	1990	114	25	0.68	1989
55	P-3142	0.39	1993	115	27	0.91	1990
56	P-1716	0.91	1992	116	28	0.91	1993
57	P-2909A	0.91	1988	117	29	0.91	1992
58	P-1	0.85	1995	118	30	0.57	1988
59	P-57	0.91	1997	119	31	0.91	1995
60	P-7	0.91	1999	120	32	0.91	1997

E-3: Pipe and Nodal data for RWDS$_0$ [Original Network]

[PIPES]						[JUNCTIONS]		
;ID	Node1	Node2	Length	Diameter	Roughness	;ID	Elev	Demand
P-2973	J-3745	J-214	185.928	40	110	J-3745	1186	0.2649468
P-809	J-212	J-214	261.8232	40	90	J-3791	1185	0.69
P-2819	J-3516	J-212	76.2	70	110	J-2703	1192	0.079484
P-3007	J-3720	J-3702	164.2872	100	95	J-3501	1171	0.352
P-3034	J-2380	J-3617	31.0896	40	130	J-3703	1175	1.552
P-2809	J-3508	J-280	36.576	40	120	J-280	1162	0.156
P-3005	J-3735	J-3720	147.828	60	110	J-3735	1174	0.0618209
P-3009	J-3702	J-3775	365.4552	125	110	J-3617	1196	0.0618209
P-1720	J-3773	J-3501	738.8352	40	120	J-2311	1202	0.3965
P-2803	J-3502	J-2703	69.7992	80	90	J-2380	1196	0.0618209
P-3098	J-3508	J-3840	1452.677	40	90	J-3831	1174	0.8
P-3126	J-3735	J-3791	160.02	70	100	J-3509	1196	0.2737784
P-2991	J-3840	J-3841	1359.103	40	110	J-3508	1163	0.0529894
P-1716	J-2312	J-2311	393.8016	80	100	J-212	1187	0.2561153
P-7	J-3507	J-3509	277	125	100	J-3516	1185	0.2561153
P-9	J-3506	J-3507	398	80	120	J-3506	1188	0.5740515
P-10	J-2297	J-2286	331.62	80	100	J-3775	1182	0.1148103
P-13	J-3735	J-3506	574.87	40	100	J-2242	1173	0.6711986
P-16	J-3799	J-3507	649.15	152.4	110	J-3720	1172	0.0618209
P-30	J-2380	J-2311	200	50	120	J-3799	1167	0.529

P-31	J-3617	J-3618	30	254	110	J-3505	1195	0.5652
P-32	J-3618	J-3703	150	40	90	J-277	1157	0.6
P-35	J-2241	J-2703	204	40	105	J-3840	1159	0.2119575
P-53	J-3516	J-3515	100	60	100	J-3618	1196	0.0618209
P-6	J-3509	J-3515	785.67	40	95	J-3515	1185	0.2561153
2	J-3509	Muyenga-TE	6422	254	100	J-3773	1177	0.2649
7	J-3831	J-3703	4394.43	70	100	J-2286	1187	0.609
11	J-3502	J-3684	126	90	95	J-214	1188	0.3444
13	J-3684	J-3505	900	60	110	J-3841	1190	0.0353262
14	J-2380	J-3502	780	40	100	J-3507	1186	0.2296206
P-3094	J-3773	J-2241	3.92	70	110	J-2241	1177	0.0441578
15	J-3773	J-2242	353.15	40	110	J-3502	1194	0.318
16	J-3840	J-2242	1000	40	100	J-3684	1188	0.894
17	J-3684	J-2311	813.9	40	90	J-3702	1186	0.177
18	J-277	J-3505	623.6	40	85	J-2297	1190	1.024
19	J-2312	J-2297	527	60	100	J-2312	1194	0.1059787
12	J-3702	J-3791	100	100	110	J-284	1173	0.53
21	J-277	J-280	334	40	100	1	1187	0.609
22	J-280	J-284	350	60	100	2	1200	0.1148103
27	J-3720	J-3799	116	110	100			
28	J-3505	2	150	60	100			
29	2	J-3791	150	100	100			
30	J-284	2	450	40	120			
31	2	1	619	40	100			
33	1	J-2286	200	110	120			
34	1	J-3506	400	70	95			
35	J-3508	J-3775	350	60	100			
36	J-3775	J-3799	350	40	110			

E-4: Pipe and Nodal data for RWDS_1 [Scenario 1]

[PIPES]						[JUNCTIONS]		
;ID	Node1	Node2	Length	Diameter	Roughness	;ID	Elev	Demand
P-805	J-3517	J-3745	595.5792	50	110	J-3768	1178	0.300273
P-3060	J-3761	J-3806	1277.417	40	130	J-3844	1176	0.176631
P-2822	J-216	J-3517	390.144	40	110	J-3745	1186	0.264947
P-804	J-193	J-216	306.9336	40	98	J-3791	1185	0.69
P-2973	J-3745	J-214	185.928	80	110	J-2703	1192	0.079484
P-809	J-212	J-214	261.8232	70	90	J-3517	1173	0.088316
P-2819	J-3516	J-212	76.2	70	110	J-3838	1171	0.56522
P-2820	J-3515	J-3519B	535.5336	60	100	J-3501	1171	0.352
P-1711	J-3617	J-3683	106.3752	50	100	J-3806	1175	0.11481

P-3007	J-3720	J-3702	164.2872	110	95	J-3703	1175	1.552
P-2979	J-3768	J-3811	732.7392	90	120	J-280	1162	0.156
P-3034	J-2380	J-3617	31.0896	40	130	J-3735	1174	0.061821
P-2809	J-3508	J-280	36.576	40	120	J-2719	1167	0.742
P-3005	J-3735	J-3720	147.828	60	110	J-3617	1196	0.061821
P-2999	J-3786	J-3728	327.3552	100	100	J-3779	1172	0.1766
P-3009	J-3702	J-3775	365.4552	125	110	J-3776	1196	0.044158
P-1720	J-3773	J-3501	738.8352	125	120	J-2311	1202	0.3965
P-2803	J-3502	J-2703	69.7992	80	90	J-3518	1172	0.6353
P-3059	J-3779	J-3761	323.6976	50	110	J-2380	1196	0.061821
P-3095	J-3777	J-3768	259.6896	50	100	J-3761	1181	0.194294
P-3097	J-3776	J-3832	1267.358	50	120	J-216	1167	0.7
P-3098	J-3508	J-3840	1452.677	50	90	J-3831	1174	0.8
P-3100	J-3755	J-3811	678.7896	100	100	J-3509	1196	0.273778
P-3114	J-3832	J-3844	2017.776	50	100	J-3508	1163	0.052989
P-3126	J-3735	J-3791	160.02	70	100	J-212	1187	0.256115
P-3132	J-3786	J-3777	266.3952	70	100	J-3683	1193	0.319
P-2907	J-3831	J-3615	767.1816	50	120	J-3786	1184	0.044158
P-3147	J-3615	J-3838	1592.58	40	120	J-3516	1185	0.256115
P-2991	J-3840	J-3841	1359.103	60	110	J-3506	1188	0.574051
P-3144	J-3755	J-3687	203.9112	50	120	J-3687	1176	0.079484
P-1716	J-2312	J-2311	393.8016	60	100	J-3811	1160	1.430713
P-2909A	J-3618	J-3692	854.3544	90	120	J-3775	1182	0.11481
P-1	J-3521	J-3522	86.868	60	110	J-3832	1192	0.0883
P-57	J-3683	J-2312	773.6	40	100	J-3521	1178	0.548
P-7	J-3507	J-3509	277	203.2	100	J-2242	1173	0.671199
P-9	J-3506	J-3507	398	125	120	J-3720	1172	0.061821
P-10	J-2297	J-2286	331.62	70	100	J-3748	1168	0.988
P-13	J-3735	J-3506	574.87	40	100	J-3728	1195	0.283
P-16	J-3799	J-3507	649.15	152.4	110	J-3799	1167	0.529
P-30	J-2380	J-2311	200	70	120	J-3505	1195	0.5652
P-31	J-3617	J-3618	30	254	110	J-277	1157	0.6
P-32	J-3618	J-3703	150	125	90	J-3840	1159	0.211957
P-35	J-2241	J-2703	204	152.4	105	J-3777	1183	0.044158
P-37	J-3844	J-3501	1500	90	120	J-3618	1196	0.061821
P-39	J-3748	J-2719	155	100	110	J-3515	1185	0.256115
P-40	J-2719	J-3521	620	50	110	J-193	1171	1.019
P-42	J-3522	J-3834	800	40	105	J-3773	1177	0.2649
P-43	J-2719	J-3519B	600	90	105	J-3519B	1186	0.211957
P-53	J-3516	J-3515	100	60	100	J-2286	1187	0.609
P-54	J-3517	J-3518	50	60	110	J-214	1188	0.3444
P-4	J-	J-3518	617.8	50	110	J-3841	1190	0.035326

	3519B							
P-6	J-3509	J-3515	785.67	100	95	J-3507	1186	0.229621
P-8	J-3520	J-3748	2065	50	100	J-3522	1167	0.300273
2	J-3509	Muyenga-TE	6422	254	100	J-2241	1177	0.044158
1	J-3779	J-3831	1145.13	40	120	J-150	1169	0.953
7	J-3831	J-3703	4394.43	90	100	J-3755	1184	0.635872
9	J-3776	J-3728	254.8	80	120	J-3502	1194	0.318
10	J-3786	J-3844	851	125	120	J-3684	1188	0.894
11	J-3502	J-3684	126	125	95	J-3702	1186	0.177
13	J-3684	J-3505	900	125	110	J-3834	1173	0.54
14	J-2380	J-3502	780	40	100	J-2297	1190	1.024
P-3094	J-3773	J-2241	3.92	70	110	J-3615	1187	0.688862
15	J-3773	J-2242	353.15	40	110	J-3520	1168	1.192
16	J-3840	J-2242	1000	40	100	J-2312	1194	0.105979
17	J-3684	J-2311	813.9	40	90	J-3692	1193	0.186
18	J-277	J-3505	623.6	40	85	J-284	1173	0.53
19	J-2312	J-2297	527	90	100	1	1187	0.609
12	J-3702	J-3791	100	100	110	2	1200	0.11481
20	J-3520	J-3516	658	40	90			
21	J-277	J-280	334	80	100			
22	J-280	J-284	350	60	100			
23	J-150	J-193	210	125	110			
25	J-3834	J-3518	750	50	100			
27	J-3720	J-3799	116	110	100			
28	J-3505	2	150	125	100			
29	2	J-3791	150	100	100			
30	J-284	2	450	40	120			
31	2	1	619	100	100			
32	J-3692	1	1104	90	110			
33	1	J-2286	200	152.4	120			
34	1	J-3506	400	152.4	95			
35	J-3508	J-3775	350	60	100			
36	J-3775	J-3799	350	40	110			
37	J-3834	J-150	1000	70	80			

E-5: Pipe and Nodal data for $RWDS_2$ [Scenario 2]

[PIPES]						[JUNCTIONS]		
ID	Node1	Node2	Length	Diameter	Roughness	;ID	Elev	Demand
P-3011	J-2241	J-3778	2214.677	70	130	J-3768	1178	0.600273
P-3022	J-3762	J-3798	444.7032	50	130	J-3737	1177	0.018832
P-805	J-3517	J-3745	595.5792	40	130	J-3844	1176	0.350631

P-3060	J-3761	J-3806	1277.417	60	130	J-3821	1192	0.7033
P-838	J-165	J-164	155.7528	70	130	J-3846	1204	0.684431
P-2822	J-216	J-3517	390.144	80	130	J-3745	1186	0.528947
P-839	J-150	J-146	594.9696	70	130	J-3791	1185	1.38
P-804	J-193	J-216	306.9336	40	130	J-2703	1192	0.15484
P-3026	J-3780	J-3763	299.6184	40	130	J-3793	1187	0.3378
P-3002	J-3776	J-3777	273.7104	100	130	J-3517	1173	0.178316
P-2973	J-3745	J-214	185.928	100	130	J-3838	1171	1.126522
P-809	J-212	J-214	261.8232	80	130	J-3501	1171	0.702
P-3012	J-3778	J-3699	551.688	70	130	J-3806	1175	0.22981
P-2819	J-3516	J-212	76.2	40	130	J-3703	1175	3.1052
P-2820	J-3515	J-3519B	535.5336	152.4	130	J-280	1162	0.326
P-1711	J-3617	J-3683	106.3752	70	130	J-3735	1174	0.121821
P-3081	J-3713	J-3793	372.7704	90	130	J-3718	1186	0.42
P-825	J-164	J-3814	504.7488	50	130	J-165	1162	3.99
P-3080	J-3713	J-3744	177.0888	50	130	J-2719	1167	1.4842
P-3007	J-3720	J-3702	164.2872	70	130	J-3617	1196	0.121821
P-2979	J-3768	J-3811	732.7392	40	130	J-3787	1207	1.041062
P-3028	J-3772	J-3718	242.6208	40	130	J-3758	1177	0.215979
P-3024	J-3736	J-3737	150.876	50	130	J-2314	1204	2.382
P-3034	J-2380	J-3617	31.0896	457.2	130	J-3779	1172	0.3526
P-2809	J-3508	J-280	36.576	90	130	J-3780	1185	0.105589
P-3005	J-3735	J-3720	147.828	152.4	130	J-3815	1190	0.5289
P-3057	J-3787	J-3846	1687.982	60	130	J-3763	1172	0.264
P-3021	J-3762	J-3718	256.6416	70	130	J-3776	1196	0.088158
P-3074	J-3752	J-3794	421.8432	80	130	J-146	1178	1.050405
P-2999	J-3786	J-3728	327.3552	80	130	J-2311	1202	0.8065
P-3009	J-3702	J-3775	365.4552	50	130	J-3518	1172	1.2653
P-1720	J-3773	J-3501	738.8352	100	130	J-3736	1186	0.5437
P-2803	J-3502	J-2703	69.7992	203.2	130	J-2380	1196	0.121821
P-3020	J-3741	J-3762	225.552	40	130	J-3761	1181	0.388429
P-3059	J-3779	J-3761	323.6976	50	130	J-216	1167	1.4
P-3092	J-3763	J-3737	479.4504	152.4	130	J-3772	1181	0.178316
P-3093	J-3737	J-3833	424.2816	110	130	J-3713	1195	0.618
P-3095	J-3777	J-3768	259.6896	100	130	J-3814	1169	1.097557
P-3097	J-3776	J-3832	1267.358	40	130	J-3831	1174	1.6
P-3098	J-3508	J-3840	1452.677	100	130	J-3509	1196	0.545378
P-3100	J-3755	J-3811	678.7896	80	130	J-3508	1163	1.112989
P-3101	J-3741	J-3780	60.3504	406.4	130	J-212	1187	0.516115
P-3102	J-3780	J-3736	437.9976	50	130	J-164	1170	1.454188
P-3114	J-3832	J-3844	2017.776	60	130	J-3683	1193	0.639
P-3120	J-3772	J-3741	172.212	80	130	J-3786	1184	0.089158

P-3126	J-3735	J-3791	160.02	254	130	J-3516	1185	0.513115
P-3132	J-3786	J-3777	266.3952	60	130	J-3506	1188	1.154051
P-2907	J-3831	J-3615	767.1816	70	130	J-3687	1176	0.160484
P-3147	J-3615	J-3838	1592.58	50	130	J-3711	1212	0.421
P-2991	J-3840	J-3841	1359.103	60	130	J-3811	1160	2.860713
P-3146	J-3687	J-3840	2706.014	110	130	J-3778	1162	0.262473
P-811	J-3520	J-3508	1042.721	40	130	J-3775	1182	0.22981
P-2830A	J-3706	J-3522	2015.338	70	130	J-3832	1192	0.1683
P-3144	J-3755	J-3687	203.9112	152.4	130	J-3829	1162	0.089158
P-3142	J-3778	J-3772	307.2384	90	130	J-3521	1178	1.0548
P-1716	J-2312	J-2311	393.8016	100	130	J-2242	1173	1.251186
P-2909A	J-3618	J-3692	854.3544	100	130	J-3720	1172	0.123182
P-1	J-3521	J-3522	86.868	110	130	J-3748	1168	1.988
P-57	J-3683	J-2312	773.6	70	130	J-3728	1195	0.563
P-7	J-3507	J-3509	277	304.8	130	J-3706	1173	5.502
P-9	J-3506	J-3507	398	355.6	130	J-3799	1167	1.0529
P-10	J-2297	J-2286	331.62	50	130	J-3505	1195	1.0352
P-13	J-3735	J-3506	574.87	254	130	J-277	1157	1.2
P-14	J-2297	J-3714	406.88	100	130	J-3840	1159	0.421957
P-15	J-3714	J-2314	401.14	100	130	J-3777	1183	0.088158
P-16	J-3799	J-3507	649.15	40	130	J-3618	1196	0.122182
P-30	J-2380	J-2311	200	90	130	J-3794	1173	0.215979
P-31	J-3617	J-3618	30	762	130	J-3515	1185	0.526115
P-32	J-3618	J-3703	150	203.2	130	J-193	1171	2.03
P-35	J-2241	J-2703	204	90	130	J-3798	1182	0.262473
P-37	J-3844	J-3501	1500	70	130	J-3773	1177	0.539
P-39	J-3748	J-2719	155	50	130	J-3519B	1186	0.431957
P-40	J-2719	J-3521	620	152.4	130	J-2286	1187	1.219
P-42	J-3522	J-3834	800	60	130	J-214	1188	0.6844
P-43	J-2719	J-3519B	600	90	130	J-3841	1190	0.070326
P-48	J-150	J-164	180	50	130	J-3507	1186	0.459621
P-53	J-3516	J-3515	100	70	130	J-3522	1167	0.600273
P-54	J-3517	J-3518	50	508	130	J-2241	1177	0.088158
P-4	J-3519B	J-3518	617.8	125	130	J-3714	1175	0.3526
P-6	J-3509	J-3515	785.67	152.4	130	J-3752	1193	0.4972
P-8	J-3520	J-3748	2065	100	130	J-3824	1213	1.798
P-48A	J-164	J-164A	0.01	355.6	130	J-150	1169	1.953
P-2830AA	J-3522	J-3522A	0.01	203.2	130	J-3755	1184	1.273587
2	J-3509	Muye-TE	6422	355.6	130	J-3502	1194	0.638
P-3088S	J-3829	J-3758	1931.75	50	130	J-3684	1188	1.74
P-3082S	J-3758	J-3713	650.45	90	130	J-3744	1185	0.444079

P-3075S	J-3713	J-3752	705	60	130	J-3702	1186	0.345
P-3140S	J-3752	J-3711	602.28	90	130	J-3699	1176	1.0364
P-3065S	J-3711	J-3717	914.7	40	130	J-3833	1173	0.315868
P-3056S	J-3711	J-3787	355	100	130	J-3762	1176	0.102989
3	J-3711	J-3824	1631.59	152.4	130	J-3834	1173	1.09
4	J-3821	J-3815	1693	40	130	J-3717	1190	0.159484
5	J-3824	J-3821	417	125	130	J-2297	1190	2.044
6	J-3824	J-3779	2154.6	203.2	130	J-3741	1184	0.22981
1	J-3779	J-3831	1145.13	254	130	J-3615	1187	1.378862
7	J-3831	J-3703	4394.43	203.2	130	J-3520	1168	3.3592
8	J-3763	J-3778	805	100	130	J-2312	1194	0.219787
9	J-3776	J-3728	254.8	80	130	J-3692	1193	0.376
10	J-3786	J-3844	851	70	130	J-284	1173	1.07
11	J-3502	J-3684	126	254	130	J-164A	1170	0.089158
13	J-3684	J-3505	900	254	130	J-3522A	1167	0.695444
14	J-2380	J-3502	780	254	130	1	1187	1.22
P-3094	J-3773	J-2241	3.92	406.4	130	2	1200	0.229681
15	J-3773	J-2242	353.15	50	130	0	Open	;
16	J-3840	J-2242	1000	70	130	0	Open	;
17	J-3684	J-2311	813.9	60	130	0	Open	;
18	J-277	J-3505	623.6	80	130	0	Open	;
19	J-2312	J-2297	527	90	130	0	Open	;
12	J-3702	J-3791	100	80	130	0	Open	;
20	J-3520	J-3516	658	110	130	0	Open	;
21	J-277	J-280	334	50	130	0	Open	;
22	J-280	J-284	350	80	130	0	Open	;
23	J-150	J-193	210	90	130	0	Open	;
25	J-3834	J-3518	750	100	130	0	Open	;
27	J-3720	J-3799	116	203.2	130	0	Open	;
28	J-3505	2	150	254	130	0	Open	;
29	2	J-3791	150	203.2	130	0	Open	;
30	J-284	2	450	110	130	0	Open	;
31	2	1	619	152.4	130	0	Open	;
32	J-3692	1	1104	90	130	0	Open	;
33	1	J-2286	200	110	130	0	Open	;
34	1	J-3506	400	125	130	0	Open	;
35	J-3508	J-3775	350	203.2	130	0	Open	;
36	J-3775	J-3799	350	60	130	0	Open	;
37	J-3834	J-150	1000	152.4	130	0	Open	;