# Intermittent Water Supply: Effective Modelling and Integration of User Behaviour

by

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The candidate confirms that the work submitted is his own and that appropriate credit has been given where reference has been made to the work of others.

## Dedication

To my loving parents, Alhaji Sirajo Muhammad and Hajiya Rabi Adabiyya Muhammad.

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# Abstract

The increase in water stress caused by climate change, population growth and crumbling infrastructure has caused many water distribution organisations in developing countries to provide users with an intermittent water supply (IWS). As a result, users receive tap water for a few hours a day, or for some days during the week, and are therefore forced to adopt certain responses to cope with such supply. This has become a hindrance to many countries in their effort to achieve goal 6 of the Sustainable Development Goals as IWS results in ineffective operation of distribution systems thereby causing in inequity in water supply to users. IWS systems are prevalent in Nigeria where access to tap water supply has decreased from 32% in 1990 to less than 7% in 2015. Causes of IWS are not always clear; it may be because a system is deliberately operated in this way, it may be due to user behaviour in poorly design systems, or it may be a combination of factors. Only a few studies have been carried out to understand the complex interrelation between modes of operation of IWS and how user behaviour affects the water distribution systems, particularly in small systems fed from tanks.

To understand this anomaly, this study models the hydraulic behaviour of a tank fed network and examines household coping strategies in response to IWS in Jigawa State Nigeria. The work aims to use the hydraulic model to simulate the interaction between IWS and user coping strategies. A mixed methods study was carried out in a residential housing estate of 505 households in Dutse, Jigawa State, Nigeria. A semi-structured household survey questionnaire was used to assess existing water supply in the estate, coping strategies and water storage options adopted by households in response to IWS. The hydraulic modelling tool

EPANET was used to develop a model of the water distribution network for the estate, and an evaluation of the network performance was carried out based on data collected from the survey.

Findings show that the distribution system provides uneven supply of tap water to households with reports of water supply duration ranging from up to 23 hours of supply to less than 1 hour as reported by households. Almost all households have adopted the use of small storage containers in order to store water for use when supply has been switched off. Some households have also installed large storage tanks fed by a private electric pump connected to the distribution mains, which was found to contribute to overconsumption from these households.

Modelling of the distribution system has shown that, although the main tank capacity may be sufficient given the typical water consumption rate of this part of the country, there are issues with low pressure across the system. The pressure was found to be lower than the standard minimum of 7m required by international guidelines and as such has been responsible for the inequity in the supply of water to the estate. Modelling results have also shown the negative effects of overconsumption on pressure values across the system. The study found that both demand driven and pressure dependent analyses can be useful tools in identifying the variation and effects of pressure within IWS distribution systems. However, low pressure systems may pose some challenges in the selection of reference pressure for pressure driven analysis. Raising the tank elevation has been proven to eliminate the occurrence of low pressure and improve service delivery. This study concludes that small systems fed by tanks must be designed to provide sufficient pressure across the distribution system to avoid the effect of overconsumption.

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## List of Abbreviations

| | |
|---|---|
| CWS | Continuous Water Supply |
| DDA | Demand Driven Analysis |
| EPS | Extended Period Simulation |
| GGA | Global Gradient Algorithm |
| GIS | Geographic Information System |
| GUI | Graphical User Interface |
| IBT | Increasing Block Tariff |
| IRA-WDS | Integrated Risk Assessment of Water Distribution Systems |
| IWS | Intermittent Water Supply |
| JMP | Joint Monitoring Programme |
| JSWB | Jigawa State Water Board |
| MDG | Millennium Development Goals |
| NUWSRP | National Urban Water Sector Reform Programme |
| NWSP | National Water Supply Policy |
| PDA | Pressure Driven Analysis |
| PDD | Pressure Driven Demand |
| PEWASH | Partnership for Expanded Water Supply, Sanitation and Hygiene |
| PRV | Pressure Reducing Valve |
| RWSSP | Rural Water Supply and Sanitation Programme |
| SDG | Sustainable Development Goals |
| SWA | State Water Agency |
| UN | United Nations |
| UNICEF | United Nations Children’s Fund |
| WDN | Water Distribution Network |

| | |
|---|---|
| WDS | Water Distribution System |
| WASH | Water Sanitation and Hygiene |
| WHO | World Health Organisation |

# Chapter 1: Introduction

## 1.1 Chapter introduction

This chapter introduces this research study. It highlights the background of the research, its aims, objectives and the scope and significance of the research. The chapter is then concluded with a brief description of the structure of the entire thesis.

## 1.2 Background

According to the United Nations, access to safe and affordable water is essential in exercising human beings' right to life (United Nations, 2015a). UN Sustainable Development Goal 6 (SDG6) calls for sustained and continuous availability of water services for everyone, requiring sustainable management of water resources, and highlighting the importance of water supply. However, population growth, climate change, aging infrastructure and inadequate investment and maintenance, has resulted in a surge in water stress (Alcamo et al., 2007). Low- and middle-income countries are more significantly affected by water stresses compared to high-income countries. Water utility companies often operate water distribution system (WDS) under intermittent water supply (IWS) conditions; allegedly as a response to the crisis in water resources. Under IWS, consumers receive water periodically for some hours during the day, or for some days during the week (Chambers et al., 2004) rather than continuously. The implementation of IWS may be a deliberate policy or it may happen because the design or operation of a network is sub-optimal. To cope with intermittency and ensure a continuous supply users adopt coping behaviours including timing activities to happen during hours of supply, the use of storage tanks and vessels so that enough water can be stored for use when supply has been switched off, and purchasing water from other sources (Galaitsi et al., 2016, Totsuka et al., 2004).

In 2010, more than 4 billion people (about 60% of the world's population) received water from piped connections into their dwelling or from public taps (WHO/UNICEF, 2012). These figures are likely to increase as nearly 1.9 billion people were said to have gained access to a piped water connection in 2015. This can be compared with the 650 million who gained access to a non-piped but otherwise improved supply (WHO/UNICEF, 2015b). In some low and middle income countries, more people have gained access to piped water connection than to any other form of improved supply (WHO/UNICEF, 2010). Access to a piped water connection means having access to a tap within the household, compound or in a public area. Available data are however inadequate to assess the extent to which this results in a consistent adequate and safe supply.

Water distribution networks are designed and constructed to deliver treated water from the water treatment plant to the end users. A WDS is essentially a hydraulic infrastructure consisting of pipes, tanks reservoirs pumps and valves. The hydraulic characteristics of the network determine the quality of the service provided to consumers. These characteristics include: pressure, flow and velocity along the pipes; and the pressure head and discharge at the user end of the system.

As a result of IWS water distribution networks are subjected to low or negative pressure conditions and water hammer – which cause physical damage and increased leakage. Leakage further reduces pressure, and low pressure tends to result in increased demand as users store and waste more water in an effort to secure continuous access. (Klingel, 2012, Lee and Schwab, 2005, Tzatchkov and Cabrera-Bejar, 2009). The result is a descending cycle of deterioration of the water distribution network (Charalambous and Laspidou, 2017). The implementation of IWS usually results in a vicious cycle (Figure 1.1) which further complicates performance of the system.

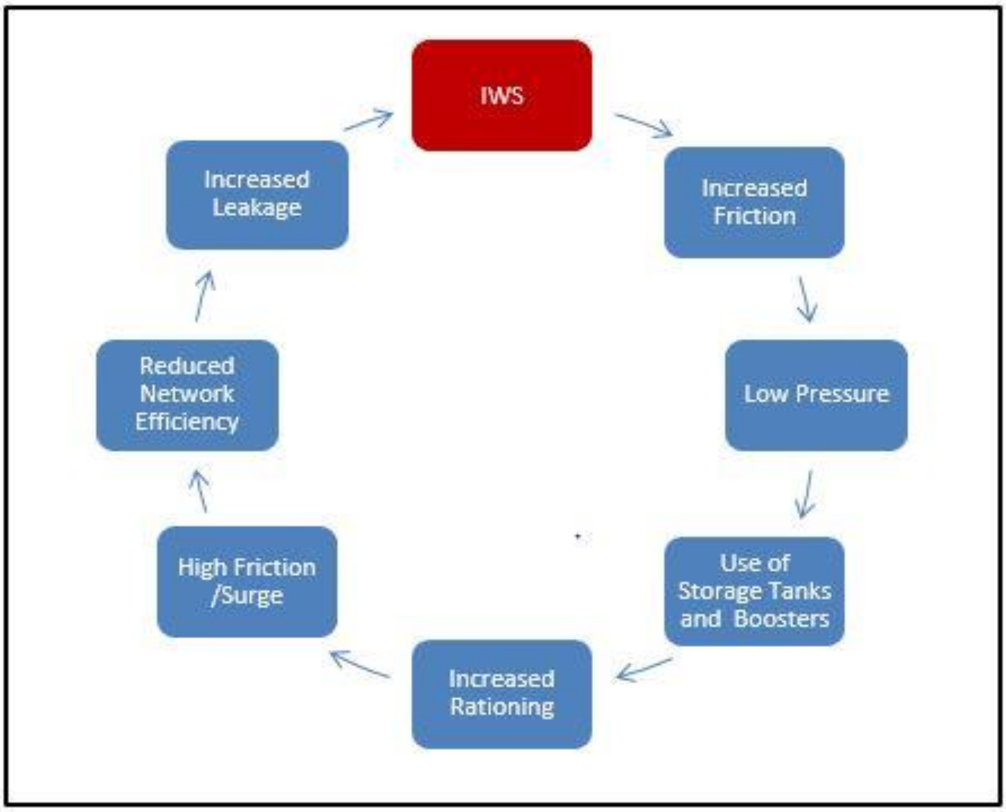



**Figure 1.1:** The Vicious Cycle of IWS (Adapted from: Charalambous and Laspidou (2017))

The solution to intermittency is multi-faceted since it is determined by both technical and behavioural considerations. Research and investigation in the field thus has to address both technical and behavioural elements.

There have been several attempts to model the operation of networks with low pressure and intermittency. Most of these evaluate the impact of minor faults like pipe breaks or routine maintenance and as such, are not considered as intermittent supply.

However, little progress has been made in modelling the operation of networks under IWS, and still less which take into account the cyclical effect of IWS on consumer behaviour. Often, IWS is case specific, making modelling results or solutions restricted to the particular cases to which they were initially intended for. It is therefore essential to have a wider perspective of how IWS operates, how it forces users to adopt coping behaviours especially in terms of consumption pattern and how the behaviour interact with the performance of the distribution system.

## 1.3 Study aims and objectives

### 1.3.1 Aims

The primary aim of this research is to develop new approaches to understand how poor system performance interacts with human behaviour in water supply networks under intermittent operating conditions. The outcome of this improved understanding would provide a basis on which to assess interventions that could improve system performance, without increasing overall water demand. The findings could potentially inform management and investment decisions to optimise interventions to improve levels of service thereby ensuring better quality of lives to consumers.

### 1.3.2 Objectives

The research has three core objectives:

Firstly, to use a case study (in northern Nigeria) to establish typical individual and household responses to intermittency, including both technical interventions and behavioural changes.

Secondly, using the same case study, to develop and test how network modelling techniques can be used to predict the intermittent flow characteristics in small scale networks operating under different demand conditions.

Finally, to use the modelling approaches to understand how interacting technical and behavioural changes to intermittent supply systems could result in improved use outcomes, and consider how these approaches could be applied to support both communities and water utility companies to effectively manage their water supply.

Specifically, this research aims to answer the following questions:

- How do households respond to intermittent water supply?
  - What coping strategies do households adopt and how are these impacted by the nature of the intermittency experienced?
- How do these responses interact with the performance of the distribution network?
- How well can modified network models predict the outcomes of intermittent supply and the associated household behaviours?
  - How do typical networks (for example in small systems in Northern Nigeria) perform under intermittent supply?
  - What consumption patterns do households produce as a result of network performance coupled with their coping strategies?

- How do the household level modifications and behavioural responses affect system performance?
- Can Engineering interventions improve service delivery in a typical case study?

## 1.4 Scope and significance of the study

The provision of adequate water supply is essential in providing good quality of life. IWS is common in many developing countries who have fall short in providing adequate water to its populace. Despite several decades of international commitment to increasing access to high quality water services IWS remains prevalent in piped water systems, particularly in low- and middle-income countries.

This study is based around a case study. The case study was selected to be both usefully representative of a typical situation which is fairly widespread and also bounded, to allow for testing of new approaches to modelling. The case study is typical of residential estates and communities which are being fed by gravity tanks and who are isolated from the central grid water distribution network. A residential housing estate in Jigawa State of Nigeria was used as a case study.

Using fieldwork as the primary source of data, the study employs mixed-methods design using qualitative and quantitative methods through surveys to assess the existing water supply service and user behaviour in response to IWS. Water distribution network modelling software were used to simulate system operation. The combined results from the fieldwork and modelling were the tools used to address the study objectives.

While the operation of intermittent water supply varies depending on local conditions, and the behaviour of households as a result of IWS could be assumed to be unique to the type of intermittency and the region where it is practiced, the study is useful in establishing the plausibility of modelling the combination of the two effects. In this study, more focus is given to the direct impact of user behaviour with more emphasis on consumption patterns and how they influence network behaviour.

Findings from this study would be useful in providing insight into the complexities and challenges associated with the implementation and operation of intermittent water supply. The application of these findings could help in the design, operation and management of systems to ensure equitable supply and hopefully provide better levels of water supply service than would otherwise be experienced during intermittent water supply.

## 1.5 Structure of thesis

This thesis is structured into eight chapters.

**Chapter 1**

The chapter provides a background of the research, its aims, objectives and the justification for the study. It also highlights the questions that the research attempts to answer.

**Chapter 2**

This chapter gives an extensive review of intermittent water supply by exploring the causes, the effects and the intervention options. It also presents some of the attempts as well as challenges in modelling IWS.

**Chapter 3**

This gives a brief description of the state of water supply in Nigeria and an overview of the country's status with regards to water stress and water scarcity. The chapter also provides an overview of water supply services in Jigawa State.

**Chapter 4**

The chapter presents the findings from a household survey on responses to intermittent water supply. The first part of the chapter provides details of the research design and methodology. The second part describes the demographic characteristics of the study sample and presents a descriptive statistic of results from the survey.

**Chapter 5**

This chapter is divided into three sections. The first section describes the background of water distribution systems modelling and the general concepts for computer simulation of such systems. The basic system elements and governing equations are also discussed. The second section describes the water distribution network (WDN) of the case study based on data collected from the fieldwork and presents some initial capacity performance assessment results. Finally, the third section describes the development of a hydraulic model of the WDN for the case study based on physical information of the system obtained during the field work. The hydraulic modelling software selected for the simulations is also briefly discussed together with assumptions considered in the development.

## Chapter 6

This chapter is presents EPANET analysis results of the case study WDN model developed in chapter five of this thesis. Both steady state simulation and extended period simulation (EPS) results are presented and discussed. The chapter also presents the application of potential strategies to introduce overconsumption and assesses the implication on the whole distribution network. Three models of the case study WDN developed based on different per capita demands are presented. Simulation scenarios and demand patterns used to set up analysis options for these models are also presented. The chapter concludes with the introduction of engineering interventions that can improve service delivery for the case study supply system.

## Chapter 7

This chapter introduces pressure driven analysis and its governing equations. It also presents the software used to carry out the pressure driven demand (PDD) analysis of the case study network. Results from the analysis are presented. The chapter presents the results of a PDD analysis using WaterGems in an attempt to evaluate nodal demand shortfall within the case study network. Limitations of PDD analysis regarding its application to IWS are discussed.

## Chapter 8

This chapter presents a general discussion, in broader details, of the key findings reported from the previous chapters. Firstly, it presents detailed discussions on results obtained from the survey of households' responses to intermittent supply. Secondly, discussions on modelling and simulation results obtained are discussed, followed by discussions on interventions to improve service delivery. Finally, the chapter concludes with key takeaways obtained from the study.

**Chapter 9**

This chapter presents the conclusions, limitations and applications of the work presented in this thesis as well recommendations for future research.

# Chapter 2: Causes, effects and problems in solving Intermittent Water Supply

## 2.1 Introduction

Water Distribution Systems (WDS) are complex, utilising infrastructure combined with management strategies. They are designed to process, store and deliver safe drinking water to consumers at all times (Mays, 1999, Walski et al., 2007). However many WDS provide intermittent water supply (IWS), which features deliberate or unintentional scheduling of breaks in the water supply, ranging from daily to weekly, with supply durations varying from as low as one hour per day to more than twenty hours per day (Ingeduld et al., 2006, Sashikumar et al., 2003, Van den Berg and Danilenko, 2011).

The main objectives of this literature review are to identify and discuss: the fundamental causal factors of IWS; the resulting implications of IWS; and the options for managing/mitigating them. This review is divided into six sections as follows: (i) the introductory section (current section), (ii) the nature and prevalence of intermittent water supply, (iii) the various causes of IWS, (iv) problems associated with IWS, (v) available options for managing intermittent water supply, and (vi) the key conclusions and recommendations.

## 2.2 Nature and prevalence of IWS

IWS is common in both low and middle income (Hardoy et al., 2001, McIntosh, 2003, McIntosh and Yñiguez, 1997, Vairavamoorthy et al., 2001) and high income countries (Cubillo, 2004, Cubillo, 2005). In many low and middle income countries, it is often deliberately employed as a demand control technique (Butler and Memon, 2005, McIntosh, 2003). It is estimated that about 30 percent of the population with piped water supply in Latin America and Africa, and more than 50 percent in Asia receive water on an intermittent basis (WHO/UNICEF, 2000, Klingel and Nestmann, 2014). Although comprehensive data on the regularity of IWS are limited, over one billion people are reported to have access to piped water in the countries where IWS is known to be common (Van den Berg and Danilenko, 2011, WHO/UNICEF, 2012). Vairavamoorthy and Elango (2002) reported that in Southeast Asia, up to 91% of water supply systems operate intermittently. A wide range of different supply durations and operational regimes have been reported. In the Middle East for example, IWS is operated in many cities only during the dry season where water is supplied for 10 to 12 hours daily, reverting to continuous supply during the wet season (Abu Amr and Yassin, 2008, Coelho et al., 2003, Korfali and Jurdi, 2007).

Figure 2.1 shows a global distribution of typical daily supply durations. These data do not reveal the number of days for which supply is available. The most severe cases of intermittency have been recorded in some parts of Asia where normal supply duration may be as low as 2 to 4 hours a day (McKenzie and Ray, 2009). Similarly in Africa, some cities record supply durations well below 10 hours a day while others only receive water for some days during the week (Van den Berg and Danilenko, 2011).

Larger cities with more complex distribution systems sometimes operate intermittent supply on a rotational basis where supply is provided to isolated sections in a successive manner. Smaller isolated distribution networks however, may be grouped together and supplied water at the same time (Kumpel, 2013). The pattern of intermittency experienced at different sections within a system may differ in both space and time. Pipe dimensions, network pressure and population density have all been shown to be associated with differences in supply durations (Sashikumar et al., 2003).

There has not been a systematic review of the causes of IWS. In general commentators have stated that the extent of IWS varies depending on the nature of the distribution system and the surrounding circumstances. Because all systems are initially designed to operate continuously, IWS is only introduced when the system is no longer operated as designed. The cause or trigger for the switch to IWS is often said to be excessive demand, high rates of leakage/pipe breaks and possibly, unplanned network expansion. Totsuka et al (2004) suggested that although IWS is a technique of rationing water quantity, it is also a technique for controlling other inputs like power, use of limited treatment chemicals and unaccounted consumption (Totsuka et al., 2004).

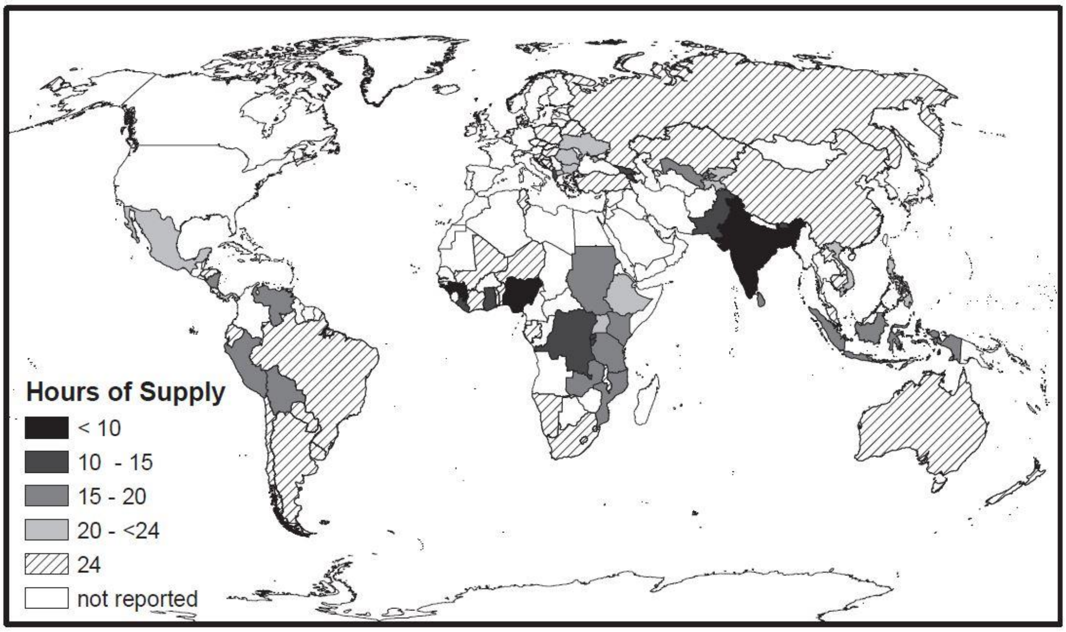



**Figure 2.1:** Supply hours recorded by utilities providing IWS services. Source: Van den Berg and Danilenko (2011)

As the rate of access to piped water connections rises, there is a risk that increased bulk water withdrawal rates, urbanization and population growth will create more challenges. IWS will plausibly become more common than continuous water supply (McDonald et al., 2011, Vairavamoorthy et al., 2008). About 375 million people in at least 45 countries (most of which are low or middle income countries) receive intermittent water supply to their households or to public taps (Van den Berg and Danilenko, 2011). It is therefore necessary to study IWS as a concept that will be an integral part of many water distribution systems especially in low- and middle-income countries. For example, there is a need to have an in-depth understanding of how users are likely to behave in response to intermittent supply and the consequences of those actions on the distribution network.

Although it is almost impossible to design a safe network for intermittency because of the risk of infiltration with untreated groundwater, the knowledge can as well be referred to right from inception or design of a WDS. There is a need to design systems so that the stresses that result in IWS can be minimised. This means much better zoning, the use of more active pressure and demand management, and a real commitment to operation and maintenance.

## 2.3 Causes of intermittent water supply

### 2.3.1 Introduction

In stable systems, where population growth is low and predictable, and infrastructure well established and well maintained, the most likely causes of intermittency are unavoidable circumstances such as natural disasters (flood damage, earthquakes and severe droughts) and human interventions such as system upgrades and routine maintenance or repairs (Solgi et al., 2015, Wagner et al., 1988). In such situations, the intermittency is temporary and supply usually resumes once these causes have ended or have been mitigated.

By contrast in systems that operate under conditions of rapid population growth and/ or inadequate operation and maintenance intermittency may be a regular occurrence characterised by continuous rationing and reduced supply duration. In such cases it is almost impossible to revert to continuous supply once intermittency is initiated. Van der Bruggen et al. (2010) argued that a number of IWS causes are interrelated such that segregating them individually becomes a daunting task. These factors combine to cause a “vicious cycle” of intermittent water supply (Charalambous and Laspidou, 2017, Ingeduld et al., 2006). The section below discusses some of the key factors that contribute to the existence of IWS in most low-income countries.

### 2.3.2 Poor governance

One major cause of water supply intermittency is poor governance. A lack of rule of law, little or no participatory decision-making, weak institutions, inequity, lack of transparency and responsibility can all result in poor decision making (Rogers and Hall, 2003). Poor governance has been associated with poor water supply in many developing countries (McIntosh, 2003) especially as it results in inadequate funding allocations to water supply infrastructural development and operation (Bakker et al., 2008, Dahasahasra, 2007, Totsuka et al., 2004, Van der Bruggen et al., 2010). The core responsibility for the mobilisation of resources towards developing water supply infrastructure with a view to ensuring adequate supply to all citizens lies with Governments, and where these are weak or corrupted investment is likely to be both inadequate and poorly targeted (Brunner et al., 2015). Insufficient resources for both investments and operations is a major constraint for many water systems (Gutierrez, 2007). Poor implementation of legislative policies (Batchelor 2009) often results in distortions in budgetary allocations in the affected countries (Lehmann, 2010, Van der Bruggen et al., 2010). Several studies have shown that aspects of poor governance contribute directly to water shortages (Giglioli and Swyngedouw, 2008, Ioris, 2012) Political influence has been shown in some cases, to hinder successful management and operation water supply systems (McIntosh, 2003, McKenzie and Ray, 2009, Seetharam, 2005).

Thus, improving water management is predicated on improving governance policy and legislation (Biswas and Tortajada, 2010, Jones et al., 2014). Governance interventions should involve empowering key institutions and stakeholders that regulate the water sector such as government agencies, civil society groups, water utilities and local communities. According Dorado (2005), such inclusive engagement among the stakeholders is vital as it ensures water supply challenges are identified from an informed viewpoint, and these are matched with adequate resource mobilisation as agreed by the stakeholders in the sector. The major advantages of this approach include effective information dissemination and awareness on the challenges in the water sector, improvement options decided based on collaborations, and consensus on sustainable water supply improvement solutions.

### 2.3.3 Population growth and urbanisation

Population growth and rapid urbanisation are two factors which are associated with intermittent water supply in both rich and poorer countries (Buchberger et al., 2008). Rapid population growth puts stress on resources including water, especially through increased demands which ultimately may lead to water scarcity (Bakker et al., 2008, Klingel, 2012, Lehmann, 2010, Myers, 2003, Totsuka et al., 2004). The increase in population is aggravated by urbanisation and the high population densities in cities (Bao and Chen, 2015, Bao and Fang, 2012, Butler, 2004, Cohen, 2006). These have been shown to place even more demand on the already limited water and sanitation services thereby exceeding the capacity of existing infrastructure (Le Blanc, 2008, Seetharam, 2005).

Most notably in many low and middle income countries, urbanisation has resulted in rapid growth of unplanned settlements (Ioris, 2012). Often, these settlements are neglected by government and usually have little or no formal sanitation and/or water supply infrastructure (Bakker et al., 2008, Cohen, 2006, Van der Bruggen et al., 2010). Some studies have attempted to offer some insight into why these areas are not serviced. Some of the reasons given include poor housing/settlement planning which hinders distribution networks (Mason, 2009, Van der Bruggen et al., 2010). However, it seems more plausible that political drivers result in conscious neglect of these communities. It is unclear to what extent unplanned settlement status contributes to water supply intermittency. Nonetheless, where planning does not take them into account, consumers in unplanned areas will certainly continue to access water in some way, and likely thereby contribute to poor performance of the network and the associated intermittency.

### 2.3.4 Climate change and land use

Climate change and land use changes are contributing to water stress. With regards to climate change, existing evidence are indicative of increases in cases of droughts and flood events in different parts of the world (Parry et al., 2007, Vairavamoorthy et al., 2008).

Droughts constitute an important factor when considering water supply. Typically, droughts results in severe reductions in water quantities from both surface and underground water (Dracup et al., 1980, Miyan, 2015, Wilhite, 2000).

Changes in land-use can result in increased runoff, and reduced retention of water in surface and underground reservoirs (Mishra et al., 2007). Deforestation results from agriculture, construction and wood production and continues apace despite increased awareness of the resultant stresses on resources (Allen and Barnes, 1985). According to Bullard (1966) and Mango et al. (2011), an increase in the area of cultivated land leads to an increase water pollution, sediment loads and surface runoff. Similarly there is an increased demand for irrigation water especially in drier seasons (Wagner et al., 2013). Settlements in urban areas have been reported to increase pollution of water resources particularly due to paved surfaces and soil compaction. This results in decreased usable surface and reduced quantity and/or quality of ground water (Van der Bruggen et al., 2010).

Several studies have also reported an increase in the frequency and duration of drought in various parts of the world (European Commission, 2012, Miyan, 2015). Impacts of drought have been experienced in some least developed Asian counties as well as in Europe. For example, in Ogun State, Nigeria, the effect of climate change resulted in droughts which dried up wells used as primary source of water for communities (Adeniji-Oloukoi et al., 2013). Similarly in Lemesos, Cyprus, experience of severe drought is reported to have led to the adoption IWS (Charalambous, 2012).

Another report by Pachauri et al. (2014) focused on the ways in which climate change will impact on water supply systems, and makes suggestions on some achievable resilient strategies. Some of these suggestions include analytical approaches for mitigating the effects of climate change, policy approaches and technology development and transfer. In some richer countries, there exists some recommendations and procedure on how extreme climate-related circumstances may be handled with an overall minimal impacts on lives and properties (Estrela and Vargas, 2012, Rossi and Cancelliere, 2013); whereas in low and middle income countries, such procedures are non-existent or inadequately defined to cope with such extreme climate events (O'Hara and Georgakakos, 2008). This is most likely because (i) climate-related events are usually not considered as significant (Danilenko et al., 2010, Oates et al., 2014); (ii) there is poor land use planning and development (Ioris, 2012); and (iii) there are little or no efforts towards addressing existing hydrological challenges and establish/invest in robust water utilities to cope with future climate-related extreme events.

### 2.3.5 Economic factors

Economic factors have financial impact on the availability and demand of water in any society. For instance, Nachiyunde et al. (2013) argued that water availability is reduced when water quality deteriorates due to industrial effluent discharge which causes pollution. Also, when economies flourish, a lot of industries are established and this increases industrial water consumption depending on the type of industry, the technology being used and the scale of operation (Bao and Chen, 2015, Bao and Fang, 2012). Another economic factor is wealth, where some studies indicate that human water consumption is likely to increase with increase in wealth (Butler, 2004, Totsuka et al., 2004, Vásquez and Espaillat, 2016). Nonetheless, Nauges and Whittington (2017) reported a weak relationship between wealth and high water demand. All these factors impose additional stress on existing water sources and infrastructure, leading to interruptions in water supply.

### 2.3.6 Poor operation and management

Another major cause of IWS is poor operation and management of the water supply system and this can be extended to poor data management. Several studies conducted have shown that poor management usually results in reduced revenue generation (Biswas and Tortajada, 2010), leads to difficulty in developing tariff plans, making it challenging for performance assessment and analysis of the water supply system (Klingel et al., 2012, Lehmann, 2010). Boland and Whittington (2000) argued that setting the right tariffs is key to ensuring effective water resource allocation thereby ensuring affordability, sustainability and effective cost recovery (Nauges and Whittington, 2017, Rogers et al., 2002). However, not all water utilities and institutions are operating in an environment where income from tariffs, plus any available public funding covers the costs of supplying water (Nauges and Whittington, 2017). In the case of low income countries, tariffs are usually too low and usually fall short of meeting operating and maintenance costs (McIntosh, 2003). Most of these costs would need to be covered by governments, cooperating partners and donors (Lehmann, 2010). However finance for operational costs is usually a low priority for governments and the result may be systematic under investment in operations and maintenance. (Biswas and Tortajada, 2010, Franks, 2005).

Chronic underfunding is often hidden because so-called 'pro poor' tariff structures exist, allegedly to provide the funds needed to operate systems adequately. The most commonly used of these is the increasing block tariff (IBT) structure which is widely used in many countries (Evans and Mara, 2011). IBT's are designed to enable consumers of high quantities of water (assumed to be the rich) to subsidise water consumed in the poor areas. Related additional funds are thought to be generated when industries subsidise domestic water consumption (Boland and Whittington, 2000, Rogers et al., 2002). In fact poor areas rarely gain from these subsidies because these areas are not receiving piped or metered services (Le Blanc, 2008, Mason, 2009). While Whittington et al. (1991), Rananga and Gumbo (2015) and Vásquez and Espaillat (2016) have highlighted the unwillingness of the poor to pay for water services they also point out that this is largely because of the high costs of connecting which act as a deterrent, and the unavailability of trunk services in many low-income settlements. The ability or inability of consumers to pay for water may therefore be said to affect the levels of service that they receive and can hence lead to intermittency in water supply.

Another aspect of water supply systems which aggravates supply intermittency is infrastructure maintenance, which is often poor in low and middle income countries (Montgomery and Elimelech, 2007). Some reports have established that poor maintenance schedules often leads to increased cost of maintenance (Buchberger et al., 2008). Poor infrastructure maintenance have been attributed to such factors which include: lack of financial resources particularly due to inadequate revenue generation; poor data management often leading to inadequate knowledge of the existing system; and little or no technical and managerial skills (McIntosh, 2003, Seetharam, 2005).

### 2.3.7 Insufficient skilled personnel

The unavailability of skilled personnel is a factor that has direct impact especially on the distribution system. It impacts such areas as planning, operation and management (McIntosh, 2003). Successful management of water supply systems is governed by effective use of technology and data management techniques which requires the skilled personnel. In low and middle income countries, there is limited data management and use of technology and where these exist, there are no skilled manpower to drive the process (Farley and Liemberger, 2005). This is particularly due to lack of expertise and failure to recognise the significance of functional databases for water resources management (Klingel, 2012). It is an establish fact that there is a general lack of appropriate technical and managerial skills required to improve water services delivery to adequately address the growing population and urban expansion in many countries (Cohen, 2006, Franceys and Jalakam, 2010, Myers, 2003).

### 2.3.8 Distribution system expansion

The importance of distribution system expansion especially in developing countries has been highlighted in the Sustainable Development Goals (United Nations, 2015b). This has been set as one of the performance indicator for water utilities in most developing countries (Van den Berg and Danilenko, 2011). However, a key issue is that these expansions are often unplanned, even so with poorly managed utility databases (Klingel, 2012). These often results in poor distribution deteriorated distribution networks. With these expansions coupled with limited available water, the capacity of the distribution systems becomes over stretched, making it incapable of performing to its hydraulic standards (McIntosh, 2003).

### 2.3.9 Unreliable power supply

Power is vital for the successful operation of water utilities especially in water pumping operations. Wong et al. (2015) reported that water distribution systems require significant input of energy. Meier (1990) argued that intermittent water supply and poor electricity distribution have some common causes as well as being closely interlinked in their impacts. In low- and middle-income countries, energy generation is itself subject to performance constraints. These may arise due to a dependency on fossil fuels which may in turn be impacted by fluctuations in local supplies and quality, or in the price of imported fuel, inadequate investment and poor management which can all result in inefficiencies and intermittency of supply. In some cases, domestic hydropower or wind power may be available but will also be subject to performance constraints and influenced by effects of climate change) (Eberhard et al., 2011, Vergara et al., 2007). Irrespective of the mode of generation of electricity, these factors play a key role in determining the production and price of electricity. Power outages or shortages are as common in the power supply as in the water network, and in turn, negatively impact on systems of water supply. Thus, in an attempt to holistically address the challenge of IWS, it becomes imperative for stakeholders in the sector to adequately define the extent to which poor electricity supply impacts on the distribution system. This would provide a platform to develop informed solutions and mitigating measures.

## 2.4 The impact of IWS

### 2.4.1 Effects on distribution networks

Water distribution networks are usually designed to operate under Continuous Water Supply (CWS) irrespective of the operational regime. They are designed with the assumption that demand is spread over 24 hours in a form of demand pattern. A common demand pattern is to assume two spikes in any 24-hour period. These spikes have ‘peak factors’ of between 2 and 3 meaning that the consumption at these times is likely to be 2 to 3 times higher than the average. These usually occurs in the mornings and evenings when water use is highest (Andey and Kelkar, 2009). Under IWS, the pattern will be totally different as peak factors are likely to occur at the start of supply when customers rush to withdraw as much water as possible for storage. Peak factors in intermittent systems range from 1.7 to 6.4 (Andey and Kelkar, 2009, Batish, 2003).

The network is designed to operate at a ‘minimum pressure’ which will be maintained irrespective of demand. Typical values are shown in Table 2.1 below.

**Table 2.1:** Minimum pressure guidelines for different countries

| Country | Minimum Pressure | Source |
|---|---|---|
| United Kingdom | 10m (14 psi) | (United Utilities, 2012) |
| United States | 14m (20 psi) | (AWWA, 2003) |
| South Africa | 20m (28 psi) | (Jacobs and Strijdom, 2009) |
| India | 7, 12, 17m (14, 17, 24 psi) for 1, 2 and 3 stories respectively. | (Batish, 2003) |

Networks operating under intermittent water supply experience an excessive variation in pressure – from extreme surge leading to presence of water hammer (Batish, 2003), to very low and in some cases, negative pressure (Lee and Schwab, 2005, Nyende-Byakika et al., 2012, Vairavamoorthy et al., 2008). The extreme fluctuations of pressure in intermittent supply exceeds acceptable design limits and leads to frequent incidence of pipe breaks and leakages. A study in Cyprus examined the occurrence of leakages in the city's distribution network which has been operating under IWS for two years. There was an 85% increase in the occurrence of pipe breaks and leakages as compared to preceding year, when CWS was operated (Christodoulou and Agathokleous, 2012). Water utility companies incur the cost burden of dealing with maintenance and repair, which as a result, reflects on the public, while water losses still increase (Totsuka et al., 2004).

The operation of a distribution network under IWS also has the effect of providing inequitable supply of water to consumers. This means that within a network, there are advantaged users – who receive water under high pressure when the supply is switched on, and the disadvantaged users – who receive little or no water for a long time after the supply has been switched on (De Marchis et al., 2011). De Marchis et al. applied a numerical model of simulating network filling process to a case study in Palermo where IWS was imposed due to water scarcity. A large number of disadvantaged users wait for up to 7 hours before they receive water when the supply is switched on (De Marchis et al., 2011). Another study also in Palermo, Italy concluded that even if available water will fulfil user demand, IWS will still provide inequitable distribution of water by reducing supply at nodes with higher elevation and increasing supply to nodes with lower elevation (Fontanazza et al., 2007). This imbalance usually increases near the end of a network design life where capacity and flow devices are unable to adequately distribute pressure (Totsuka et al., 2004). The use of head loss devices such as valves and orifices in the operation and maintenance of IWS systems will improve the system to provide more equitable supply to consumers (Batish, 2003). However, employing such strategies involves the use of more human resources and in turn more costs to the utility.

### 2.4.2 Health implications of IWS

The presence of low or negative pressure encourages ingress of pathogens and other contaminants via breakage points, resulting in the delivery of contaminated water and posing a serious potential public health risk to consumers (Totsuka et al., 2004, Trussell, 1999). In 1996, in Delhi, India, a typhoid fever outbreak was thought to be caused by a combination of IWS in distribution networks located close to sewer pipes (Yepes et al., 2001). The risk of contamination was further evaluated by (Kumpel and Nelson, 2013), who examined networks operating under both CWS and IWS in India. Their results showed that 31.7% of tap samples from IWS contained traces of *E. Coli* as compared to 0.7% of tap samples from CWS networks. Another study also showed similar results where 27% to 76% of samples from taps under IWS were found to contain traces of faecal coliforms (NEERI, 1994) as cited by (Vairavamoorthy et al., 2008). Intermittency compromises the potential of otherwise safe ‘improved’ piped water systems to provide ‘safely managed’ water supplies, in accordance with the spirit of SDG 6.1. As a result, more people than estimated might be receiving unsafe water supply from otherwise improved sources.

Vairavamoorthy, alongside others, developed a model called Integrated Risk Assessment of Water Distribution Systems (IRA-WDS) which could be used to determine contamination risks in IWS systems (Vairavamoorthy et al., 2007b). According to the authors, reasonable results were obtained when the model was tested on a distribution network in India, showing how IWS can have serious health implications.

The use of storage tanks adopted by households in order to cope with IWS has also been associated with increasing the risk of contamination between delivery and usage points (Elala et al., 2011, Tokajian and Hashwa, 2003). A number of studies conducted all over the word were listed in a review by (Lee and Schwab, 2005) of the health risks linked to IWS. The studies all indicated a correlation between IWS and elevated risks of exposure to pathogens and gastrointestinal illness.

### 2.4.3 Impact on user demand

It is usually assumed that IWS occurs in response to inadequate water resources to deliver continuous supply (Christodoulou and Agathokleous, 2012, Vairavamoorthy et al., 2007a). A number of commentators suggest that IWS could be regarded as an alternative technique for water demand management (Iskandarani, 2002, Joshi et al., 2002, Vairavamoorthy et al., 2008). However, there seems to be a lack of strong empirical evidence that supports such suggestions.

By contrast, there is evidence that operation of distribution networks under IWS results in significant changes and some increases to user demand patterns. In essence, users that receive continuous water only draw from the network when they are in need because it is readily available. However, those that receive water intermittently will tend to draw as much water as they can when it becomes available in order to fill their storage reservoirs with enough water to satisfy them after the supply has been switched off (Batish, 2003, Kumar, 1998). As a result, higher peak factors are created in the networks operating under IWS with up to 3.2 times as compared to CWS (Klingel, 2012). One of the causes for this increase is that users usually throw away unused left-overs in order to refill their reservoirs with fresh water once supply resumes (Batish, 2003, McIntosh, 2003), resulting in wastage and increase in unnecessary use of water (Kumar, 1998, Lee and Schwab, 2005).

In an analysis of household water use however, Nauges and Whittington showed that even when increased supply results in increased water use, the scale of the effect is small (Nauges and Whittington, 2010). Iskandarani concluded that household water consumption does not significantly change with IWS even if piped water is the major source of water (Iskandarani, 2002). By contrast, a study in four Indian cities found an increase of up to 27.5% consumption when CWS was switched to IWS (Andey and Kelkar, 2007). However, the researchers concluded in a subsequent article that not much difference in consumption was observed as long as water demand was satisfied in both CWS and IWS, noting that further research is needed in order to determine the actual effects of IWS and CWS on household water demand and consumption, especially in slums and smaller urban cities (Andey and

Kelkar, 2009). A more recent study in China however, contradicted with the findings and generalizations above. The study found that IWS of 1 to 6 hours a day results in lower consumption (33.6 – 59.7 $Lc^{-1}d^{-1}$) as compared CWS where 71.4 $Lc^{-1}d^{-1}$ was consumed (Fan et al., 2014).

### 2.4.4 Economic impact of IWS

Whenever IWS is implemented, households bear the burden of coping. The costs of IWS include installation of private tanks and booster pumps (Vairavamoorthy et al., 2008). In addition, households are sometimes forced to reschedule their daily activities to correspond with anticipated supply hours. This result in missed school or work, as well as sleep disruption where households have to wake up late at night (Madanat and Humplick, 1993, Totsuka et al., 2004). These and other coping behaviours are very similar to those adopted by that portion of the population without access to piped water. This, as argued by Evans (2007), is caused by the "long standing inability of utility and city managers and their advisers to plan and implement water and sanitation systems which respond to the reality of the lives of the urban poor" (Evans, 2007).

At the same time, water utility companies also bear loss of revenue as a result of decreased water sales. The increased cost of maintenance and repair arising from IWS will be transferred to customers either in the form of increased water tariffs or further deferred essential maintenance and further service decline (Totsuka et al., 2004).

Additional cost include those to locate and repair pipe breaks and leakages that have not been reported (Charalambous, 2011b). According to a study, an estimated €300,000 worth of revenue was lost in Cyprus as a result of 2 years of IWS, with an additional €365,000 and €325,000 spent for additional overtime expenses and leakage repair cost respectively (Charalambous, 2011a).

Water utility companies may also experience other direct losses due to water meter under-registration. Evidence form a study suggest that the use of private tanks in addition to low flows and pressures, causes the flow meters to “under-register” the quantity of water going through them. The study further reported that after the installation of Pressure Reducing Valves (PRVs) in a particular network, there was a 50 percent increase in apparent losses in the network. These losses were related to whether the PRVs were actually reducing or increasing the pressure; meter errors often reduce in some places when PRVs become stable and causes the pressure to increase (De Marchis et al., 2013). This casts doubt on the reliability of PRVs in managing the pressure of a network and might actually be the leading cause of the losses observed.

Indirect costs are also incurred by both water utility companies and consumers. For example, water utility companies have to bear with public frustration, doubt and declining payment of bills from customers. At the same time, customers have to bear with the inconvenience of finding other sources of water like staying in long queues and the cost of local treatment of water. A study in Kathmandu, Nepal, highlighted that, in addition to costs incurred in fetching and storing of water, a significant amount of money is further spent by households on local treatment of water for domestic use (Katuwal and

Bohara, 2011). The amount spent for monthly water bills reportedly doubled in some cases (Pattanayak et al., 2005).

While the costs are large, they are difficult to assess and quantify (Effah et al., 2013). Overall however, the direct and indirect costs of IWS challenge the common position that IWS is a rational economic response to water shortages (Shrestha and Buchberger, 2014).

## 2.5 User behavior in coping with IWS

IWS causes inconvenience to households and results in the adoption of coping behaviours to satisfy water needs. A number of studies have been carried out to identify and understand the behavioural strategies households adopt in coping with IWS – the understanding of which is vital in successful implementation of water demand management (Rosenberg et al., 2007). For example, a survey in India, identified some behaviours common to households receiving periodic water supply (Joshi et al., 2002). All the surveyed households had overhead tanks installed with most of them using electric pumps to pull water from the distribution network. Although all the households were content with the quality of water provided, 35% were found to further treat their water before drinking, while 58% threw away excess stored water whenever supply became available. Remarkably, even with these inconveniencies, households said they were “satisfied” with as little as three hours of supply so long as the pressure remained sufficient.

Another study in India, this time of 700 households with in-house connections, identified a number of coping strategies which include, but are not limited to storage and pumping (Zérah, 2000). In a more recent survey in Jordan, Rosenberg et. al. (2008) surveyed household behaviour in coping with IWS and came up with “16 supply enhancement and 23 demand management actions available to urban residential water users”. Some of these behaviours include installation of ground or overhead tanks, installation of storage containers in toilets, installation of residential water treatment facilities, drilling of boreholes or tube wells etc. However, the authors noted that these behaviours, in and of themselves, do not give a general conclusion as the characteristics of each behaviour varies within households (Rosenberg et al., 2008). Interestingly, a study in Accra, Ghana reported very similar coping strategies being adopted by households (Nyarko et al., 2008).

Although households usually find alternative ways to manage water shortage, it can be concluded that the adoption of these behaviours will directly or indirectly have impact on both users and utilities.

While user behaviour might as well be considered to be a cause of intermittency, it results in the deterioration of the distribution system. However, it is as a result of intermittency that a number of user behaviour are adopted by households. User behaviour in response to IWS is therefore one of the focal points that govern the level of intermittency in a system and as such, needs to be further studied.

## 2.6 Challenges in managing IWS

### 2.6.1 Introduction

There are two sets of responses commonly proposed to address the challenges of IWS:

i. Firstly, the development of strategies and tools to effectively design, model and analyse distribution systems. This is assumed to be possible even when intermittency occurs in networks which were originally designed to operate continuously (Abu Amr and Yassin, 2008, Pathirana, 2010, Vairavamoorthy and Elango, 2002, Vairavamoorthy et al., 2008).
ii. Secondly, to convert operations from intermittent to 24/7 supply. This approach considers IWS to be unacceptable and as such any attempts at mitigating the impacts other than achieving a continuous supply status would be seen as intermediate and transitory (Klingel and Nestmann, 2014, McIntosh, 2003, Myers, 2003).

These two approaches are discussed in more details in the following sections.

### 2.6.2 Design

Some commentators posit that IWS is inevitable in some contexts and it is therefore essential to explore suitable means of designing or redesigning these systems (Batish, 2003). This position would ensure that systems designed from inception, avoid problems encountered when intermittent supply is operated on systems designed for continuous supply (Batish, 2003, Totsuka et al., 2004, Vairavamoorthy et al., 2008). The primary aim of designing IWS systems becomes centred on achieving equitable water supply (Totsuka et al., 2004, Vairavamoorthy and Elango, 2002). However, there is very limited information on optimum design specifications because of the small base of empirical research conducted to date (Effah et al., 2013).

Generally, IWS systems are designed based on continuous supply peak factors, usually within a range of 2 and 3 (Andey and Kelkar, 2009, CPHEEO, 1999, Vairavamoorthy and Elango, 2002). In these cases peak factors are computed by dividing 24 hours by the equivalent supply duration (in hours) per day (Abu-Madi and Trifunovic, 2013, Batish, 2003, Pathirana, 2010, Vairavamoorthy and Elango, 2002, Vairavamoorthy et al., 2001), with values usually ranging from 1 to higher values above 6 (Abu-Madi and Trifunovic, 2013, Bose et al., 2012, Dahasahasra, 2007). Designing for IWS at appropriate pressures results in larger  pipe sizes and would have cost implications, a trade off that is rarely considered in economic assessments of IWS (Bose et al., 2012).

A method by (Chandapillai et al., 2012) was put forward for the design and improvement of systems providing intermittent supply. This method proposed that whenever there is a network expansion, the head at the source must be regulated to sustain the acceptable level of demand satisfaction. However, this method is rather more theoretical than practical. The first major step taken towards realising a standard procedure for the optimal design and operation of IWS systems was the development of the first set of guidelines by Vairavamoorthy and Elango (2002). The proposed guideline, which was to be accompanied by a software, was developed in an attempt to resolve the issues raised by WDN designers who otherwise had no option but to design systems expected to operate intermittently as though they were continuous (Totsuka et al., 2004, Vairavamoorthy et al., 2001, Vairavamoorthy et al., 2008). Unfortunately however, as at time of writing this review, neither the guidelines nor the software have been released for public access.

A procedure that involves the use of false tanks/reservoirs was proposed by (Batish, 2003), where demand nodes were replaced by theoretical reservoirs. However, this procedure was found to be inapplicable on larger water distribution networks (Batish, 2003, Mohapatra et al., 2014, Muranho et al., 2014). Furthermore, the model was only effective if the dimensions of the tanks/reservoirs for all the households were similar (Trifunović and Abu-Madi, 1999).

The lack of a standard method for the design, analysis and simulation of IWS systems may be due to the fact that IWS is recognised as having significant disadvantages. These relate both to performance, particularly in terms of water quality and cost, if they are to be designed to withstand the resultant pressure waves of intermittency (Dahasahasra, 2007, Klingel and Nestmann, 2014, McIntosh, 2003, Myers, 2003, Vairavamoorthy and Elango, 2002).

### 2.6.3 Conversion

In contrast to the design of systems for intermittency, the alternative approach is to convert intermittent water supply to 24-hour supply. To successfully achieve this conversion sustainably, temporary solutions must be replaced by long term permanent ones. The key is the elimination of key causal factors. It is worth mentioning that, as has been discussed earlier, there are a great number of possible causes of IWS and each case may be caused by one or a combination of the factors mentioned – making conversion of IWS continuous one of the most difficult water supply problems faced by utilities and concerned stakeholders.

Several attempts and recommendations have been made to convert IWS to continuous and within these, a few have gone further to suggest approaches that focused on improving or eliminating the key causal factors. The importance of functional distribution network was identified by Dahasahasra (2007) as critical while Klingel and Nestmann (2014) highlighted management of data as key. Biswas and Tortajada (2010) and McIntosh (2003) emphasised that the key factors necessary for conversion are governance and tariffs. One of the drawbacks of these studies is that certain factors earlier mentioned were not considered as critical. For instance, challenges in power supply and climate change have not been addressed amongst critical factors as such, no suggestion was made on how to ensure robustness of the converted systems against these factors.

A successful attempt, was carried out in which three cities of Karnataka, India who were receiving IWS service were upgraded to continuous supply (World Bank, 2013). The intervention was associated with high capital investment costs although it is not clear if significant costs savings could have been achieved through the adoption of more incremental interventions.

## 2.7 Modelling and analysis

Modelling and analysis of WDNs is carried out to design new networks and/or to assess and improve the efficiency and reliability of existing ones through the development of different operational scenarios. Models use demands as input to solve well-known hydraulic equations and provide typical hydraulic parameters such as flow rate, water pressure and velocity (Walski et al., 2007).

Modelling and analysis of distribution networks operating IWS is however a more complex process. Determining user demand is difficult because of the effects of behavioural responses such as private pumps, household water storage and the resultant waste (De Marchis et al., 2010, Mohapatra et al., 2014). Leakage as a result of intermittency is another difficult parameter to include in design analysis because there may be variations between the night and day flows which are dependent on available network pressure (Ndirangu et al., 2013).

The majority of existing software for network analysis include the ability to carry out demand-driven analysis. This can be useful for IWS. In systems with potential for low or negative pressure; the demand driven analysis can be used as a tool to understand the variation of nodal pressure across the network as a result of change in consumption at certain nodes.

For demand-driven models, the assumption is that there is adequate pressure at every demand node which ensures that the water supplied meets consumer demand (Giustolisi and Walski, 2011, Wagner et al., 1988). Although demand driven analysis still gives the outcome of system performance with regards to pressure, it gives a very little information on how demand is affected by change in pressure. In the case of IWS systems, where the water available to consumers is dependent on the available pressure and demand might not necessarily be met by the available supply (Andey and Kelkar, 2009, Batish, 2003, Chandapillai et al., 2012, Giustolisi and Walski, 2011). For this reason pressure-driven models may be more appropriate for modelling IWS For this, relationships between outflows and the nodal pressure must be established

(Chandapillai, 1991, Germanopoulos, 1985, Giustolisi et al., 2008, Lee et al., 2015).

Distribution networks operating intermittently are usually described as "pressure deficient" where they lack the pressure required to supply adequate water to consumers. Several approaches have been suggested for analysing pressure deficient systems (Ang and Jowitt, 2006, Elhay et al., 2015, Mahmoud et al., 2017, Muranho et al., 2014, Shirzad et al., 2012). However, while all systems operating under intermittent supply tend to be pressure deficient, not all pressure-deficient systems are intermittent. As a result, a number of pressure dependent analysis options have only been tested on non IWS systems.

A number of pressure driven mathematical models that first introduced the flow-pressure relationship in pressure deficient systems were studied by Gupta and Bhave (1996). The study concluded that although other models show reasonable results, the model established by Wagner et al. (1988) gave the most accurate flow estimates. For this reason, it has been the most widely accepted model for analysis of systems that are deficient in pressure (Giustolisi and Walski, 2011). The conditions below were postulated by Wagner et al. (1988) for their mathematical model to be true.

- Supply is zero for nodes with pressure value below the minimum pressure.
- Full demand is met when nodal pressure is above desired pressure.
- Actual nodal supply is less than demand and is given by equation 2.1 provided nodal pressure falls between minimum pressure and desired pressure.

$$Q = Q_{rd}\left(\frac{H-H_m}{H_s-H_m}\right)^{\frac{1}{n}}, \qquad (2.1)$$

where: $Q$ is the actual supply, $Q_{rd}$ is the required demand, $H_s$ is the desired pressure, $H_m$ is the minimum pressure, $H$ is the actual nodal pressure and $\frac{1}{n}$ is 0.5. However, calibration can be used to calculate the values of $\frac{1}{n}$ (Cheung, Van Zyl, and Reis 2005).

In recent years, a number of modelling software or extensions to existing software have been developed with specific tools for modelling and simulation of pressure deficient systems including WaterGems (Bentley Systems Inc, 2017), EPANET-Emitter (Pathirana, 2010), EPANETpdd (Morley and Tricarico, 2008), WDNetXL (Laucelli et al., 2015) and OOTEN (Van Zyl et al., 2003). A recent study attempted to integrate both EPANET and SWMM especially in modelling the flow transition in pipes – a case which is very common to IWS. The study, noting the suitability of SWMM at better simulating network charging phase, developed a converter programme which converts EPANET input files into that of SWMM. This meant that EPANET would be used draw the network and the input files then converted to SWMM in order to run the network charging phase (Kabaasha, 2012). Although positive results were obtained from the study, it only however showed the viability of the converter and did not go ahead to model a real network with intermittent operation. To date none of these software packages have been specifically modified to model and simulate the operation of systems under IWS.

Furthermore, even where used for sub-optimally operated networks, many packages have not been tested in contexts that are widely found in low and middle-income settings. For instance, small scale, stand-alone networks fed by gravity from a single header tank sometimes supplemented by pumping are a very common approach to providing water to communities (Herrera et al., 2018). A number of studies have looked at these stand-alone small scale WDNs in terms of optimising their operations, or testing design and analysis strategies but none of these studies include intermittency (Alperovits and Shamir, 1977, Costa et al., 2000, Farmani et al., 2005, Wu et al., 2008a).

As highlighted in 2.5 above, IWS results in certain coping behaviours from users which contribute to the vicious cycle of intermittency. User behaviour should therefore be considered in the modelling and analysis of IWS systems. To date, knowledge on approaches that links behaviour to modelling and analyses of IWS systems remain sparse, as such further studies are needed.

## 2.8 Conclusions

The major argument against the move to continuous supply is the relatively high cost. In the longer term however, it seems plausible that such investments come with relatively high returns in terms of long term savings and should thus attract the interest of governments, donors and cooperating partners (Biswas and Tortajada, 2010, Franks, 2005). Furthermore, consumers should also be motivated by improving levels of service, hence achieving continuous water supply.

This suggests that rather than lack of funds, poor governance and administration, even though not usually considered in water assets and resource studies, is a key factor for water supply irregularity that impacts every single other factor (McIntosh 2003; Blair 2005; Biswas and Tortajada 2010). Recognizing the intricate idea of this and the other causal elements, it becomes imperative that interdisciplinary methodologies are utilized to create coordinated solutions for water supply irregularity and intermittency. These interdisciplinary methodologies should therefore carefully consider the following points in order to fully understand the complexity of IWS and to proffer lasting solutions that provide improved levels of service:

1. Raising awareness on the challenges and costs attributable to intermittent water supply; it is expected that this awareness will drive the demand for improving the supply among stakeholders in the water industry.
2. Identifying the major external factors which cause water supply intermittency and proffering sustainable ways to address them. The significance of the factors and the ways they occur differently in various scenarios, however, addressing these factors is likely to impact on the reduction or minimisation of the effects of internal causal factors thereby allowing the system to self-reset.
3. Understanding the complex interrelation between coping mechanisms and system performance. For example, there is a need to address and have a more in-depth understanding of user behaviour. This is because it is a two-phased system in that it is both a causal factor of intermittent supply, as well as coping response mechanism.

This review has highlighted the multifaceted relationship between human behaviour and hydraulic network performance and the need for further investigation in terms of understanding behaviours and being able to model the network, as well as the challenges of modelling IWS systems. The review also argues that it is important to pay significant attention on the impact of IWS on consumers and modes of analysis to ensure better understanding of the complex nature of operating intermittent water supply systems. Furthermore, there is a need to consider modes of operations of case specific systems of IWS in order to provide another perspective on the challenges of operating IWS.

## 2.9 Identified gaps in literature

A few studies have studied household coping strategies as a result of IWS. However, up till the time of writing this thesis, no literature was found to assess household coping strategies for small isolated off-grid distribution systems being fed by tanks trough the action of gravity. Very little is also known on the consumption pattern created by households who receive intermittent form of water supply and the consequent feedback on system performance. While most modellers use a default consumption pattern for 24-hour supply, it is crucial that consumption patterns for users receiving intermittent supply be used in modelling and simulation in such systems. This will provide better insight in efforts towards managing IWS or in converting to 24-hour supply.

There is a need to further explore the interrelation between user response and system performance in the context of IWS which could inform both engineering and non-engineering interventions. No study was carried out to identify which coping strategies have direct impact on the performance of the distribution system, as well as the effects of these strategies on other users. Very little is also known on IWS simulations which assess system performance based on varying user responses which are unique to households receiving intermittent supplies.

To fill these gaps, this study aims to examine user behaviour in response to intermittent water supply, identify critical strategies affecting system performance, and use modelling to tools to assess and proffer interventions that improve levels of water supply service. The outcomes will contribute to enhance improvement of intermittent water supply services, thereby providing improved levels of service and helping communities achieve Sustainable Development Goal 6.2, which aims to provide universal and equitable access to safe and affordable drinking water particularly in vulnerable circumstances.

# Chapter 3: Water supply services in Nigeria

## 3.1 Introduction

This chapter briefly discusses the general water supply situation in Nigeria and presents some of the water policies implemented by the government with regards to the water supply and sanitation sector. Water stress and water scarcity were also introduced and a review of how they vary across geographical regions in Nigeria is broadly presented.

At the end of the chapter, the case of Dutse Metropolitan region of Jigawa State is presented, showing how the impacts of the overall situation is reflected on the ground.

## 3.2 Status of water access in Nigeria

### 3.2.1 Access to improved water

According to Nigeria's Bureau of Statistics, access to improved source of drinking water increased from 61% in 2010 to 67% in 2015. Disaggregating from a geopolitical point of view, South West Zone of the country recorded the highest percentage of households with improved main source of drinking water (82.0 percent), closely followed by South East and South South with 76 percent and 73 percent respectively. The lowest was North West with 58 percent (National Bureau of Statistics (NBS), 2018)

With regards to safely managed water source, access was between 15 percent and 20 percent in 2015. Only 31 percent of the population had access to improved water at their premises. Of houses with access to improved water at the premises, more than 16 percent received intermittent supply. The quality of water in these houses varied during the rainy and dry seasons with most contamination occurring during the rainy season (Andres et al., 2017).

About 69 percent of the population of Nigeria had access to improved water, in 2015. Access rose by 29 percentage points between 1990 and 2015, with rural areas having the most increase (32 percentage points) in coverage. In fact, the rate of new access during the 25 years to 2015 was outstripped by population growth. Urban areas only saw an increase of 5 percentage points through the same period (WHO/UNICEF, 2015a). In general, Nigeria is seen as a very poor performer; having started the MDG period with relatively high access within Sub Saharan Africa the country has fallen behind, despite relatively high levels of investment.

### 3.2.2 Access to pipe water supply on premises

While it is good news that a significant increase in access to improved water was recorded at national level between 1990 and 2015, perhaps a rather worrying situation is the access to pipe water supply on premises, which reduced from 12 percent in 1990 to a mere 2 percent in 2015 (Joseph-Raji et al., 2019). The effect of this was seen more in urban areas as rural areas had almost no access to piped water supply. The main causal factors for this alarming decrease in access to piped water to premises may be attributed to rapid urban expansion, insufficient investment and lack of service expansions due to institutional constraints (Andres et al., 2017). As a result, households are faced with health and contamination issues as they are increasingly forced to seek alternative means of getting water through water vendors or by unregulated drilling of personal boreholes (Macheve et al., 2015).

On average the population receives less than 50 litres per capita per day and experiences inconsistencies in supply durations (Macheve et al., 2015). Nigeria falls below average WASH rates when compared to other countries in Africa (WHO/UNICEF, 2015a).

**Institutional framework of the Nigerian of water sector**

Nigeria, being a Federal Republic, comprises 36 states and the Federal Capital Territory (FCT). The responsibility for water resources and water delivery is shared amongst the three levels of government namely; the Federal Government (FG); the State Government (SG) and the Local Government Authorities (LGAs).

### *3.2.3* The Federal Government

The FG, through the Federal Ministry of Water Resources (FMWR) is responsible for the development and management of national policies and guidelines on water. It oversees the management and supervision of water resources – which include allocation to states and approval of water development projects. It is also responsible for conducting research and surveys, monitoring and evaluation as well as funding and supporting national water development projects with the aim of providing a conducive environment that encourage both government and private participation.

Twelve River Basin Development Authorities (RBDAs) manage water resources, gather water related data and manage irrigation. The RBDAs were created following the introduction of Degree 25 of 1976 (RBDA Act, 2004). Although the act has stated various purposes of the RBDAs, perhaps the most notable is their involvement in building multiple dams across the country which are used for supply of potable water and for irrigation.

The FG, through the FMWR, is also responsible for operation and management of the National Water Resources Institute (NWRI). Founded in 1985, the NWRI is tasked with conducting research associated with major water resource projects and for training of professionals in the water sector. It is also charged with water resource management planning and development of river basins. Over the years however, effective functioning of the institute has been challenged by a variety of factors such as inconsistent funding, inadequate equipment and insufficient skilled manpower.

### 3.2.4 The State Governments

Presently, all the 36 states of Nigeria and the Federal Capital Territory have state-owned water boards, water utility companies and corporations responsible to the management of water supply (Macheve et al., 2015). Generally referred to as State Water Agencies (SWAs), they are responsible for the construction, operation and maintenance of water supply systems for urban, semi-urban and in some cases, rural areas of their respective states. They also issue licenses to private suppliers for delegated service delivery and monitor water quality. This latter function creates conflicts of interests since SWAs act as both regulator and supplier in some cases. SWAs are generally managed by the SGs through a State Ministry of Water Resources. Few States have water laws that recognise the participation of stakeholders in policy planning, regulation or service delivery.

A recent study on the performance of SWAs in Nigeria revealed serious challenges faced by the sector. One challenge amongst many is rapid and unplanned urbanization. The report concluded that significant investment is required to support SWAs in supplying water to the population who otherwise pay higher rates to purchase water through other alternative water providers (Macheve et al., 2015). Tariffs are fixed by state policy and most SWAs are subsidised by SGs. Even so, most are not able to fully cover operational costs resulting in serious under investment and system deterioration (Ohwo, 2016). IWS is a common manifestation of this systemic under investment (World Bank Group, 2019). On current trends Nigeria is unlikely to meet the SDG targets and achieve 100 percent coverage for water and sanitation (Oloruntoba et al., 2019).

### 3.2.5 The Local Government Authorities

The Local Government Authorities (LGAs) are responsible for the provision of water supply and sanitation to rural areas (Macheve et al., 2015). They are tasked with the responsibility of establishment, operation and maintenance activities of water supply points, communal tanks and standpipes, as well as open wells and hand pumps. However, only a few LGAs have enough funds and human capacity to effectively manage these tasks (Ohwo, 2016). As such, SGs often take over these activities through the State Ministries of Water Resources.

## 3.3 Water supply policies in Nigeria

The Federal Government of Nigeria established the National Water Supply Policy (NWSP) in 2000. NWSP defines the water supply services of the country. It promotes

"*the provision of sufficient potable water and adequate sanitation to all Nigerians in an affordable and sustainable way through participatory investment by the three tiers of government, the private sector and the beneficiary*."

With the aim of addressing the challenges faced by urban areas regarding water supply and sanitation, the Federal Government, together with the World Bank, introduced the National Urban Water Sector Reform Programme (NUWSRP) in 2004. The reform was primarily targeted at improving water supply in urban regions, as well as ensuring feasibility of existing water supply utilities (FMWR, 2016). In rural areas, the policy relating to improved water and sanitation services as highlighted by millennium development goals (MDGs) was also established in 2004 under the National Rural Water Supply and Sanitation Programme (RWSSP). To ensure continuity of the RWSSP which terminated in 2015, the Partnership for Expanded Water Supply, Sanitation and Hygiene (PEWASH) programme was established with the intention of improving water supply coverage to a minimum of 57% by 2030. PEWASH is specifically aimed at achieving SDG-6.1 and 6.2 targets for water and sanitation by the year 2030 through construction of new water schemes in rural regions.

## 3.4 Water stress

Water stress may simply be defined as the total pressure that all water withdrawal imposes on available renewable freshwater resources.

According to the UN's Food and Agriculture Organization, water stress is determined as:

*”the ratio of total fresh water withdrawn to the total renewable freshwater resources in a particular country or region, after considering the water needed for sustaining the natural environment.”* (Food and Agriculture Organization (FAO), 2020).

Currently, more than 2 billion people around the world are said to be affected by water stress and this figure is expected to increase over the coming years (FAO and UN-Water, 2018). Water stress affects every country in various dimensions as even within countries, there are spatial variation of available freshwater resources. Figure 3.1 below shows the level of water stress for countries around the world.

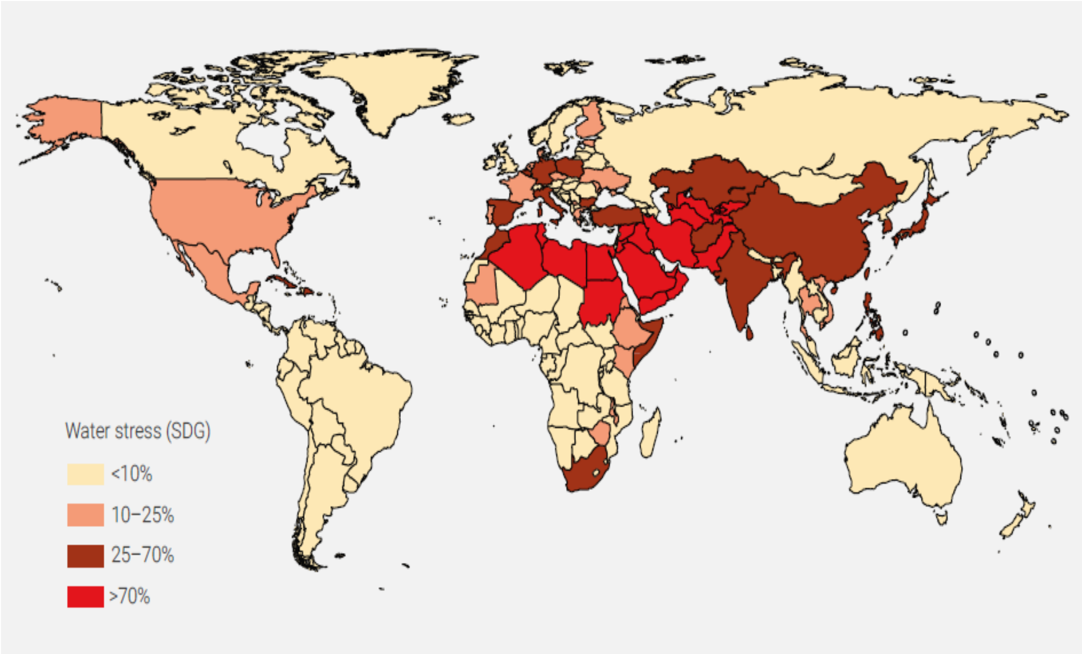



**Figure 3.1:** Levels of water stress by country (%) (2000-2015) Source: (FAO and UN-Water, 2018)

As can be seen form the figure 3.1 above, Nigeria, and in fact most countries in sub-Saharan Africa, do not fall within the range of water stressed countries. Theoretically, these countries have sufficient availability of fresh water but are however, unable to harness these resources to provide adequate safe water to satisfy their demands. A type of 'effective' water stress results, where citizens do not have access to the requisite levels of water services, despite the overall availability of the resource. There is very limited information regarding the variation of water stress across the geographic regions in Nigeria. Perhaps what is more daunting is the challenge faced by governments and utilities in implementing water management strategies to provide safe and sufficient water supply.

Competent water management is required, including policies that efficiently control supply and demand of water. For example, improving efficiency in water use for agriculture and food production will reduce excessive water consumption while cities can improve their response to water leakage and manage consumer behaviour.

## 3.5 Water scarcity

### 3.5.1 Introduction

The United Nations defines water scarcity as that point where the quality or supply of water under prevailing institutional conditions, is impinged upon by the cumulative impact of all users, consequently resulting in demand from all sectors, including environmental, not being satisfied (UN WATER, 2007). The concept of water scarcity may be relative and hence, can be found at any level of demand or supply. Scarcity may be as a result of an alteration in mode of supply (for example, due to climate change) or mainly caused by human social impact (Pereira et al., 2009). Regardless of the cause, water scarcity has significant impact not only on human lives but on the environment as well.

A study in 2015 estimate that around 4 billion people experience water scarcity of at least one month each year. Among these, up to 500 million people experience severe water scarcity (Mekonnen and Hoekstra, 2016). Water scarcity therefore poses great challenges to many programmes such as the United Nation’s effort on improving human access to water as indicated in the Sustainable Development Goals.

Water scarcity can be said to be ‘physical’ or ‘economic’.

*Physical water scarcity* usually occurs when the available freshwater resources become insufficient in meeting all demands. Most often, physical water scarcity is more prevalent in arid regions (Molden, 2007). Recently, the overdevelopment of hydraulic infrastructure have contributed in the creation of artificial water scarcity even in places where water resources are seemingly abundant (Giordano et al., 2019). Physical water scarcity is often characterised by pollution and drying out of rivers, receding groundwater and increased conflicts due to competition in water withdrawal.

*Economic water scarcity* happens when there is insufficient investment in providing water or when the demand for water outweighs the available human capacity. Economic water scarcity is prevalent in most countries of sub-Saharan Africa as can be seen in figure 3.2 below.

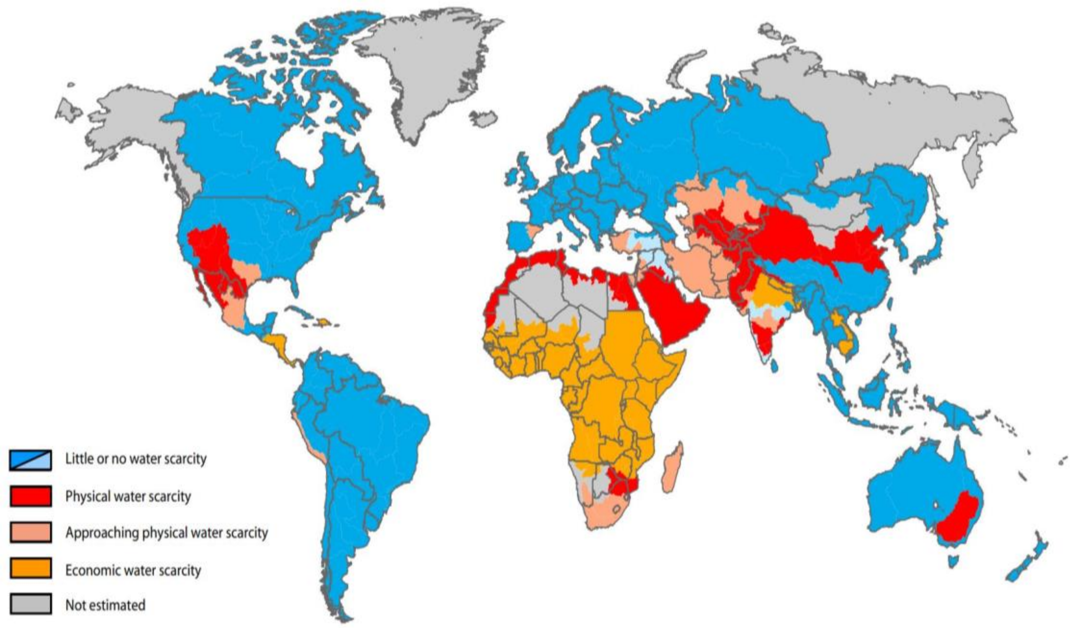



**Figure 3.2:** Areas of physical and economic water scarcity (Source: Molden (2007))

Economic Scarcity subjects people to difficulties in getting enough water for both domestic and agricultural use because of the lack of adequate infrastructure enough to satisfy their demands. Indicators of economic water scarcity may include the inability of existing infrastructure to equitably distribute water due to factors such as operation and institutional incapacities. Countries are classified as “economically water scarce” when they have enough renewable water resources but would need to make significant investments in water infrastructure to harness the resources for consumption (Rijsberman, 2006).

### 3.5.2 Physical water scarcity in Nigeria

In Nigeria, physical water scarcity may be more of a problem in the north than in the southern part of the country. The North, being mostly a semi-arid region and falling into the Sahel and Savanna climatic zones, has significantly lower annual rainfall than the southern part of the country (Ogungbenro and Morakinyo, 2014). For example, the annual average rainfall of 3800 mm in the south significantly decreases to around 650 mm in the extreme north (Ishaku and Majid, 2010).

Perhaps in response to the natural scarcity of rainfall, more than two thirds of the major dams and reservoirs in Nigeria, including the three largest in the country (with estimated capacity of 18.6 billion cubic meters) are located in the North (Oyekanmi and Mbossoh, Youdeowei et al., 2019). They are used for several purposes which include drinking water supply, irrigation and hydro-electric power generation. This higher volume of storage represents a significant investment and should have a positive influence on water security in the northern areas. The high numbers also suggest that water is available since it can be collected and stored across the country. The problem might be how to use this collected water to satisfy the demand.

There has been no evidence in literature that suggests Nigeria, or perhaps the northern part of the country is severely affected by physical water scarcity.

### 3.5.3 Economic water scarcity in Nigeria

Compared to physical scarcity, economic scarcity may be the more important factor in water resources management in Nigeria. The effects are regionally disaggregated, and these variations are related to various factors including systemic underinvestment in northern regions. The north is generally poorer than the south despite having larger population (National Population Commission (NPC) [Nigeria] and ICF, 2019). Despite this, allocations from the Federal Government are disproportionately directed to the south (National Bureau of Statistics (NBS), 2020b). These allocations are largely associated with investments in oil abstraction - oil, which is the country's primary source of income, is produced in the south. Also, due to oil related industrial activity, internally generated revenue from the south is more than that from the north (National Bureau of Statistics (NBS), 2019). The overall effect is that the north is economically disadvantaged.

A 2020 poverty survey report indicated that the north had the highest number of people living below the national average poverty line as can be seen in figure 3.3. For example, 87% of the population in Jigawa State live below the average poverty level while only 14% of the population of Anambra State in the south, live below the poverty line (National Bureau of Statistics (NBS), 2020a).

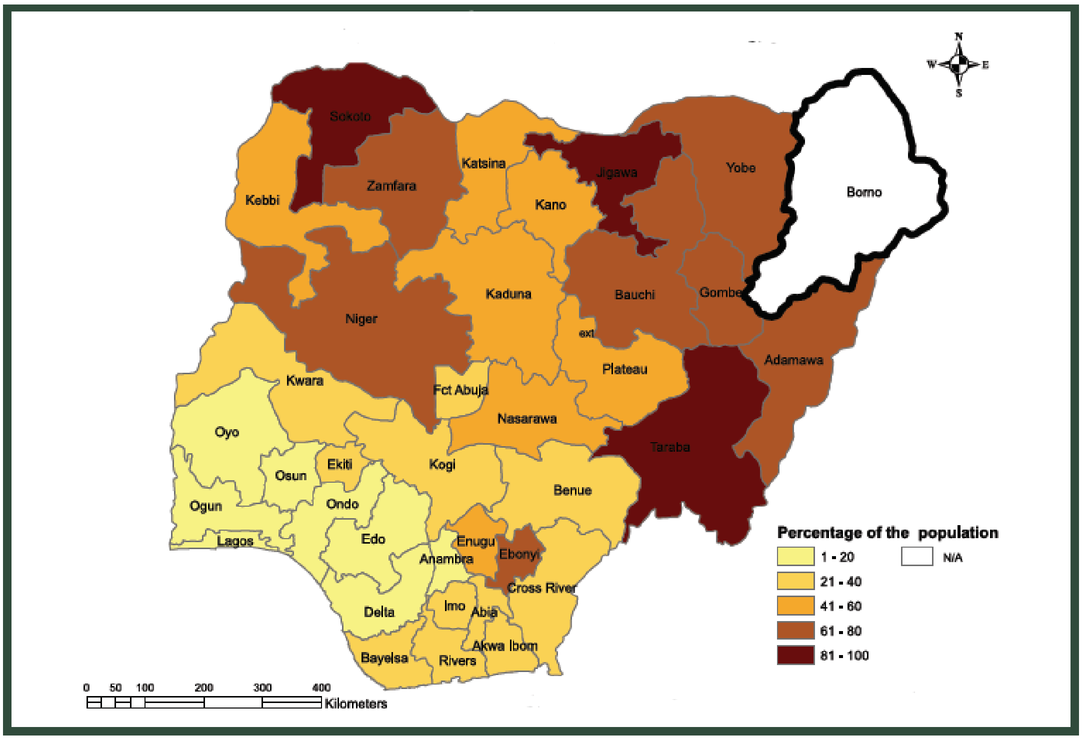



Figure 3.3: Nigeria poverty headcount rate, percentage of population Source: (National Bureau of Statistics (NBS), 2020a)

The cumulative effect of these economic factors is that investments in water services in the north are lower than average and certainly lower than would be required to secure universal access to services. This in turn is a significant contributor to economic water scarcity of the region. With the high number of dams currently located in the north, perhaps investment was only focused in water storage while not much consideration was given to distribution. The natural tendency for the northern part of Nigeria to experience more water shortage is exacerbated by socio political and political decision-making.

These findings are confirmed by data that shows disaggregated levels of access to piped water supplies – as previously mentioned, the north experiences worse levels of access and higher levels of poor quality access, beyond what might be expected simply as a result of physical water stresses.

## 3.6 Water supply in Dutse, Jigawa State

Dutse, in Jigawa state, is typical of the context of northern Nigeria in terms of access to water services. This area experiences water shortages at household level, which are often said to be attributable to physical water stress but could conceivably be associated with poor management and economic scarcity.

The city (see Figure 3.4), with an estimated population of 153,000 is the capital of Jigawa State (National Population Commission, 2006).


**Figure 3.4:** Map showing Dutse city in Jigawa State of Nigeria

The Jigawa State Water Board (JSWB), commissioned by the Ministry of Water Resources in 1991, supplies ground water to the Dutse metropolitan region. The water supply system provides consumers with water intermittently a minimum of two times per week. It consists of 19 pumping stations, 121 boreholes with submersible pumps ranging from 1-7.5 hp in capacity. Centrifugal booster pumps boost water to various storage tanks. Data from the water supply system presented in Table 3.1 was obtained from the operational records of the JSWB. The Shuwarin main water works and Gidan Ihu pumping stations produce a combined daily capacity of 524,160 litres per day, which is channelled to a 1068 $m^3$ capacity hilltop steel reservoir through an 8 km transmission pipeline. Table 3.2 shows the water supply data for Dutse metropolis. The region consists of 11 pumping stations namely: Burtilan, Garu, Yankatako, Model, New market, Mechanic village, Malam Inuwa Dutse estate, Mobile base, Takur site, Takur adua and Kachi. The collective capacity from these stations is 1,277,568 litres per day. The entire Dutse municipal therefore has a daily production capacity of 1,801,728 litres per day.

Disaggregating the total supply capacity of the state water board with regards to the population, the utility can only be capable of supplying 11.22 litres per person per day. This is below the minimum required, thus highlighting the level at which the state is facing economic water scarcity. Furthermore, as with characteristics of economic water scarcity, the apparent lack of adequate investment in infrastructure suggests that the state water board will not be able to equitably distribute the available water to the populace.

To achieve safe and equitable water supply, and manage economic water scarcity, more investment is needed in water supply infrastructure. This must be a combination of infrastructure that will support storage as well as distribution. In addition, effective management strategies should be put in place to ensure these investments are properly maintained and operated to avoid recurring system failure.

**Table 3.1:** Water supply data of main water works in Dutse

| S/N | Pumping station | No. of boreholes | No. of pumps | Average yield of pumps (l/s) | Average operating hours of pumps (hours) | Daily water production (litre per day) | Target Reservoir | Capacity of Tank (litres) | Type of tank |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Shuwarin main water works | 12 | 12 | 4 | 24 | 345,600 | Hilltop Tank | 720,000 | Surface (steel) |
| 2 | Gidan Ihu | 16 | 16 | 3.1 | 16 | 178,560 | Shuwarin main water works | 270,000 | Surface (steel) |
| | Total | | | | | **524,160** | | | |

**Table 3.2:** Water supply data of Dutse Metropolitan region

| S/N | Pumping station | No. of boreholes | No. of pumps | Average yield of pumps (l/s) | Average operating hours of pumps (hours) | Daily water production (litre per day) | Target Consumer | Capacity of Tank (litres) | Type of tank |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Burtilan | 7 | 7 | 1.7 | 16 | 97,920 | Burtilan, Fagojil, Shagari quarters, Katangare, Garki and Dutse metropolis | 200,000 | Surface (Steel) |
| | | | | | | | | 90,000 | Overhead (Steel) |
| 2 | Garu | 5 | 5 | 1.2 | 16 | 69,120 | Garu Emirs palace, Marabusawa and Dutse metropolis | 90,000 | Surface (Steel) |
| | | | | | | | | 60,000 | Overhead (Steel) |
| 3 | Yankatako | 1 | 1 | 2.4 | 16 | 138,240 | Hakimi road and Dutse metropolis | - | - |
| 4 | Model | 13 | 13 | 2.15 | 10 | 123,840 | Gida dubu and Dutse metropolis | 180,000 | Surface (Steel) |
| | | | | | | | | 22,500 | Overhead (Steel) |
| 5 | New market | 3 | 3 | 1.87 | 16 | 103,680 | New market | 22,500 | Overhead (Steel) |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 6 | Mechanic village | 2 | 2 | 1.6 | 16 | 92,160 | Dutse metropolis | 22,500 | Overhead (Steel) |
| 7 | Malam Inuwa Dutse estate | 6 | 6 | 3.1 | 16 | 178,560 | Dutse metropolis | 270,000 | Surface (Steel) |
| 8 | Mobile base (744) | 4 | 4 | 2.1 | 16 | 120,960 | Dutse metropolis | 180,000 | Surface (Steel) |
| 9 | Takur site | 8 | 8 | 2.1 | 16 | 120,960 | Dutse metropolis | 180,000 | Surface (Steel) |
| | | | | | | | | 90,000 | Overhead (Steel) |
| 10 | Takur adua | 8 | 8 | 2.3 | 16 | 132,480 | Dutse metropolis | 180,000 | Surface (Steel) |
| | | | | | | | | 90,000 | Overhead (Steel) |
| 11 | Kachi | 6 | 6 | 1.73 | 16 | 99,648 | Dutse metropolis | 180,000 | Surface (Steel) |
| | | | | | | | | 90,000 | Overhead (Steel) |
| | Total | | | | | **1,277,568** | | | |

## 3.7 Chapter summary

Nigeria's performance with regards to access to water is poor, where only 2 percent of the population have access to pipe water supply on premises. The Federal Government is responsible for policy making and regulations while the State Governments are responsible for the supply of water through the State Water Agencies.

Nigeria is not considered as a water stressed country with only mild signs of physical water scarcity at drought prone regions. However, evidence suggest that a significant proportion of the country is affected by economic water scarcity. The northern part of the country, despite having more dams than the south, shows more symptoms of economic water scarcity. This is largely attributed to geographical, economic and socio-political disadvantages that hinder effective and equitable supply of water in the region.

Jigawa state is also not excluded from the effects of economic water scarcity. The state water board has a capacity to provide only 11.22 litres per person per day, thus suggesting gross underinvestment in the water supply sector. Effective water management strategies will have to be implemented along with significant infrastructural investment in order to put the country on track to meet the SDG goal on water supply.

# Chapter 4: Assessment of Household Response to Intermittent Water Supply (A case study of Jigawa State)

## 4.1 Introduction

This chapter describes research that was designed to assess how households in Dutse town response to intermittent water supply. A mixed methods approach was used, deploying both qualitative and quantitative methods in a case study framework. In this chapter the approach to the case study is described and details of the data collection approach is provided. Methods used for data analysis are summarised. The chapter presents the results of this phase of the research, describing household behaviours in the case study area in response to intermittent water supply conditions. It concludes with a discussions and summary conclusions which will be used in the second phase of this thesis.

## 4.2 Survey objective

The objective of this chapter is to assess households' responses to intermittent water supply within a case study area. This will provide a holistic view of a system providing IWS and inform on the characteristics of both system and its mode of operation, as well as households and their responses.

The findings in this chapter will also be used as data information points and to justify assumptions in the subsequent chapters of this thesis.

## 4.3 Research approach, design and strategy

A research design describes the overall structure through which a research is carried out and defines the steps involved in answering a research question which include how data is captured and analysed. It comprises of the conceptual framework, the unit of study, and the tools used to collect and analyse the data required (Punch, 2014).

Yin (2014), defines research design as a logical order that connects data to original research question. The research approach used in this study is the mixed methods where different design methods were employed for data collection.

### 4.3.1 Mixed methods design

The design method used for this study is the mixed methods which, according to Johnson and Onwuegbuzie (2004), combines within the same study, both qualitative and quantitative methods of research. Mixed methods, in addition to utilizing the strength of both qualitative and quantitative research methods, also compensates for their weaknesses hence providing a better understanding of a problem than using either methods on their own (Punch, 2014, Creswell, 2014).

Furthermore, Greene et al. (1989) described mixed methods design as

> *"those that include at least one quantitative method (designed to collect numbers) and one qualitative method (designed to collect words), where neither type of method is inherently linked to any particular inquiry paradigm".*

This study was a mixed methods survey where a variety of data collection techniques were involved. Semi-structured observations, structured questionnaires and key informant interviews were used as research tools for data collection. The quantitative phase of the study focused on household characteristics, supply duration and water storage. Discrete choice surveys were also used to obtain household's preference and perception on water supply level of service. Discrete choice surveys are used to elicit participants preference by asking them to rank, choose or rate between multiple scenarios (Bowling, 2014). This would help in understanding household's perception of level of service and their preference for improved service.

On the other hand, qualitative methods were used to obtain background information on the area of study and also included key informant interviews with operators of the water distribution system to provide information on water supply the levels of service from the supplier's perspective.

Within mixed methods, this study applied the convergent parallel design.

### 4.3.2 Convergent parallel design

This is a mixed methods design where both qualitative and quantitative data are collected and analysed at the same time during a research process and results are merged to form an overall interpretation (Creswell and Plano Clark, 2011). This design goes by a number of names which include simultaneous triangulation (Morse, 1991) and convergence model (Creswell, 1999) amongst others. Figure 4.1 below shows the graphical procedure for implementing a convergent parallel design.

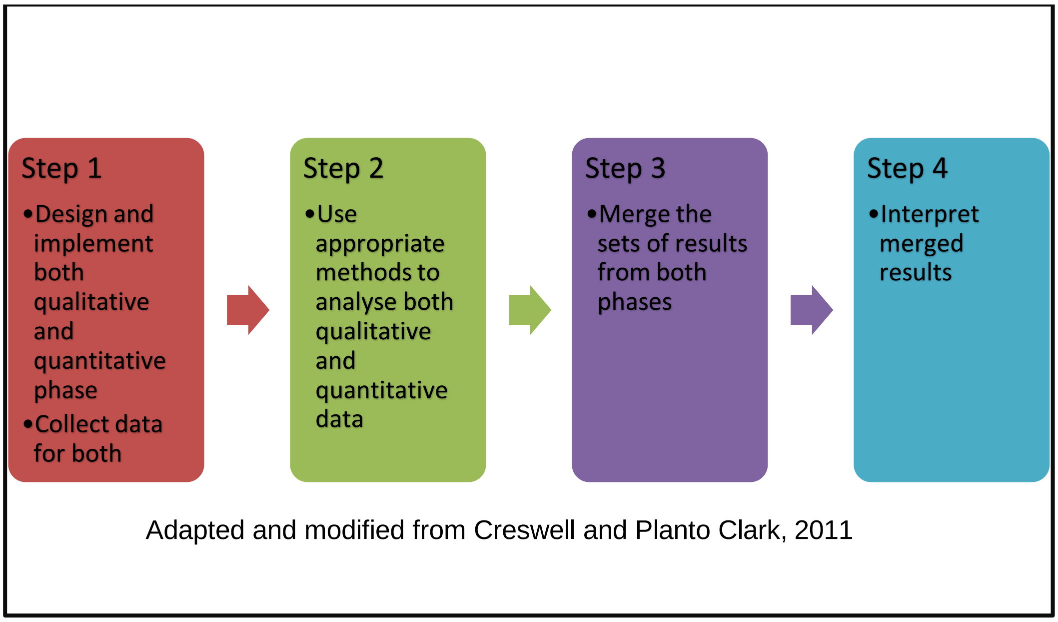



**Figure 4.1:** Steps for implementing convergent parallel design

Data collection for this study was carried out simultaneously. The qualitative phase was used to provide a general understanding of the water supply situation in the study area and households' responses as a result of the type of supply they receive. The quantitative phase was used to measure how much water is being stored by households in response to IWS.

### 4.3.3 Case study research approach

A case study research approach was employed specifically in order to gain an understanding of a particular area of study. Usually, case study research strategy is suitable for answering the "how" and "why" aspects of a research question (Yin, 2014).This approach, using suitable methods and data, allows for carrying out thorough investigation of a selected case in its *"real world"* context (Punch, 2014). The case study approach was used in both qualitative and quantitative phases of this study as the main aim was to have an understanding of coping strategies employed by households of a specific type of settlement in response to intermittent water supply.

## 4.4 The study area

Jigawa state is one of the nineteen Northern states of Nigeria with a population of about 4.3 million people (NBS, 2013). Jigawa State experiences wet season (from June to September) as well as dry season (from October to May). The region is characterised by undulating land topography with the northern part comprising of sedimentary rocks while the southern part comprises of the basement complex. Access to improved sources of drinking water was 56% in 2007 with an average household size of 6.6 persons in 2010 (NBS, 2013). Jigawa State Water Board is the State Water Agency (SWA) that is responsible for the supply of pipe borne water to the state.

In order to understand households' water storage and coping behaviour in response to intermittent water supply, this study was carried out at Inuwa Dutse Housing Estate of Danmasara district in Dutse local government of Jigawa State, Nigeria, as can be seen in Figure 4.2 below.

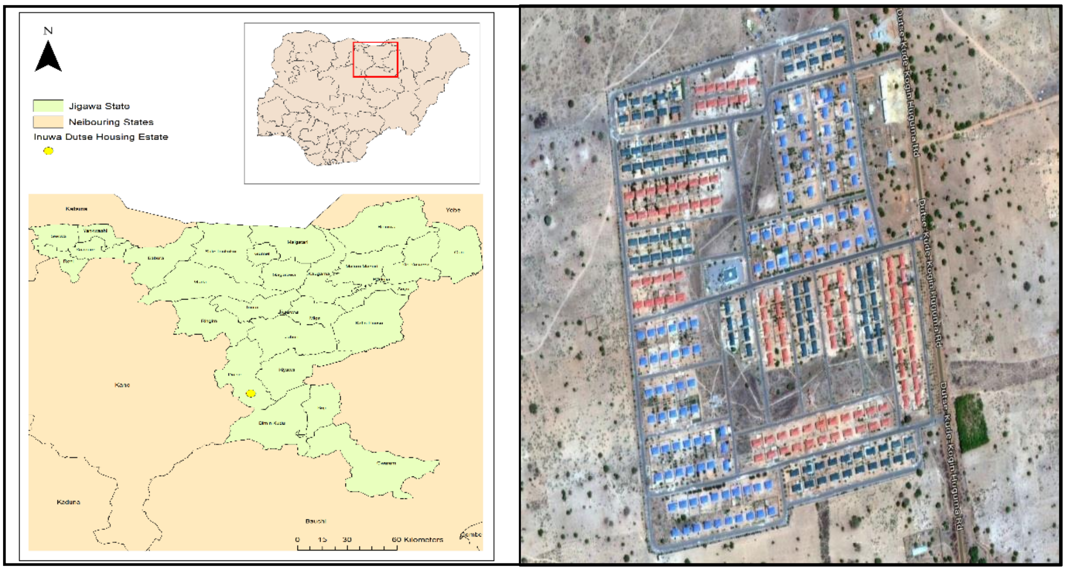



**Figure 4.2:** Jigawa State, Nigeria and the study area (Source: Bayero University GIS Lab 2016)

The site was chosen to provide a bounded case study area which can be isolated from any effects apart from the effects of IWS. The estate consists of 505 households comprising of one, two and three bedrooms. The estate is a typical development using what is generally referred to as the “sites and services” model (Mayo and Gross, 1987) and is commonly found on the periphery of cities and towns in Nigeria and other similar locations. The estate was built in 2009 and was intended for government civil servants.

The basis for the selection of this case for study was based on certain considerations which were both practical as well as methodological. The conditions that encouraged the selection of this case study are as follows:

- The case study area represents a typical residential setting now commonly found in urban and peri-urban areas in Nigerian towns and cities where water supply services are similar.

- Household locations, water sources and water distribution network can easily be identified and plotted.
- Ability to compare and relate findings to other similar communities.
- Ease of communication as the researcher speaks the same local language as the participants.

## 4.5 Ethical approval and risk assessment

The University of Leeds approved this study through the Ethical Committee of the Faculty of Engineering and the Faculty of Mathematics and Physical Sciences (MaPS). Prior to survey, participants were approached and given information sheets and asked whether they were willing to participate in the study. They were given the chance to ask for further clarification as well as the opportunity to withdraw at any time during the survey. All participants that agreed to take part in the survey were given consent forms to sign before commencement of the interviews. Permission was also sought from the participants before any pictures were taken during the interview. Hard copies of data collected were stored in a secure location while soft copies were stored in an encrypted storage device and immediately uploaded onto the University of Leeds M-drive.

As part of the requirements set out by the University of Leeds in order to obtain ethical approval, a risk assessment was carried out using the University risk assessment tool. Areas of possible risk and mitigating measures were identified to ensure a safely executed fieldwork.

## 4.6 Household survey

### 4.6.1 Introduction

The main tools used in the household survey were structured household questionnaires and semi-structured observations.

Prior to the survey the survey, the researcher visited the local mosque and met with the Imam. Details of the research were discussed and the Imam who, being the community leader, was able to announce during prayer sessions that a study was going to be carried out in the community. This was important as it gave the community some level of information about the survey prior to formal introduction by the researcher. To avoid the possibility of participants feeling obliged to participate in the survey due to influence from the Imam, the Imam clearly informed them that participation was completely voluntary and that they were free to withdraw from the survey at point.

### 4.6.2 Selection of participants and sampling frame

To get a fair representation of the case being studied, there is a need for participants to be selected in a survey. A sampling frame is therefore needed to make this selection. A sampling frame can be defined as a list of likely persons that can participate in a study (Fowler, 2008). In this study however, households are the main units of analysis instead of individual persons.

The sampling frame for this survey was therefore all the households within Inuwa Dutse Residential Estate. The estate is a typical development using what is generally referred to as the “sites and services” model (Mayo and Gross, 1987) and is commonly found on the periphery of cities and towns in

Nigeria and other similar locations. Because the case study is a planned residential estate, the researcher was able to obtain a sketch paper map of the area from the State ministry of works and housing where all households were identified with their assigned numbers. To further eliminate sources of error, the researcher used Google Earth (http://earth.google.com) and QGIS (QGIS Development Team, 2016) to identify, locate and create a map of each of the households in the study area. This was then used as a guide in participant selection and sampling.

### 4.6.3 Primary unit of analysis

In this study, the primary unit of analysis was the household, where all members of the household typically use the same source of water. There is a need however, to further clarify the term “household” as it can affect how measures such as water use, storage and household population are interpreted.

Households in this study can be made up of families which are nuclear, extended or multi-generational. Because of factors like migration and nature of work, families can additionally be categorised into split households, where members of the family who normally live in the household also live somewhere else. In this study therefore, a household was defined as a group of persons who, in addition to living and eating together, share the same water source. Taking this into consideration, this survey only considered persons who have lived in the house for more than six months to be included in the analyses.

In each household, women were the most preferred choice for interview as they usually handle household chores that involve the use of water. However, in most of the cases during the study, most women were unable to participate as they had to seek permission from the head of the family before they can be interviewed. As a result, whenever a female respondent was not available for the interview, the head of the household was then interviewed. In situations where neither the head nor the mother was available, the most senior adult member of the family was interviewed.

English language was the primary means of communication for the interview. In a small number of cases where the participants did not fully understand some English terms, the local language "Hausa" was used. The researcher could fluently speak this language and hence, there was no need for an interpreter.

### 4.6.4 Sample design

Generally, water supply to households is dependent on a number of factors which include household type, distance of household from source, and household elevation. One distinct feature of this case study area is that it is comprises of one, two- and three-bedroom houses which are distributed in clusters across the study area as can be seen in Figure 4.3 below. Because the geographic location of the households affects the hydraulic properties for water supply, it was assumed that this factor will likely influence household's responses to the type of supply they receive.

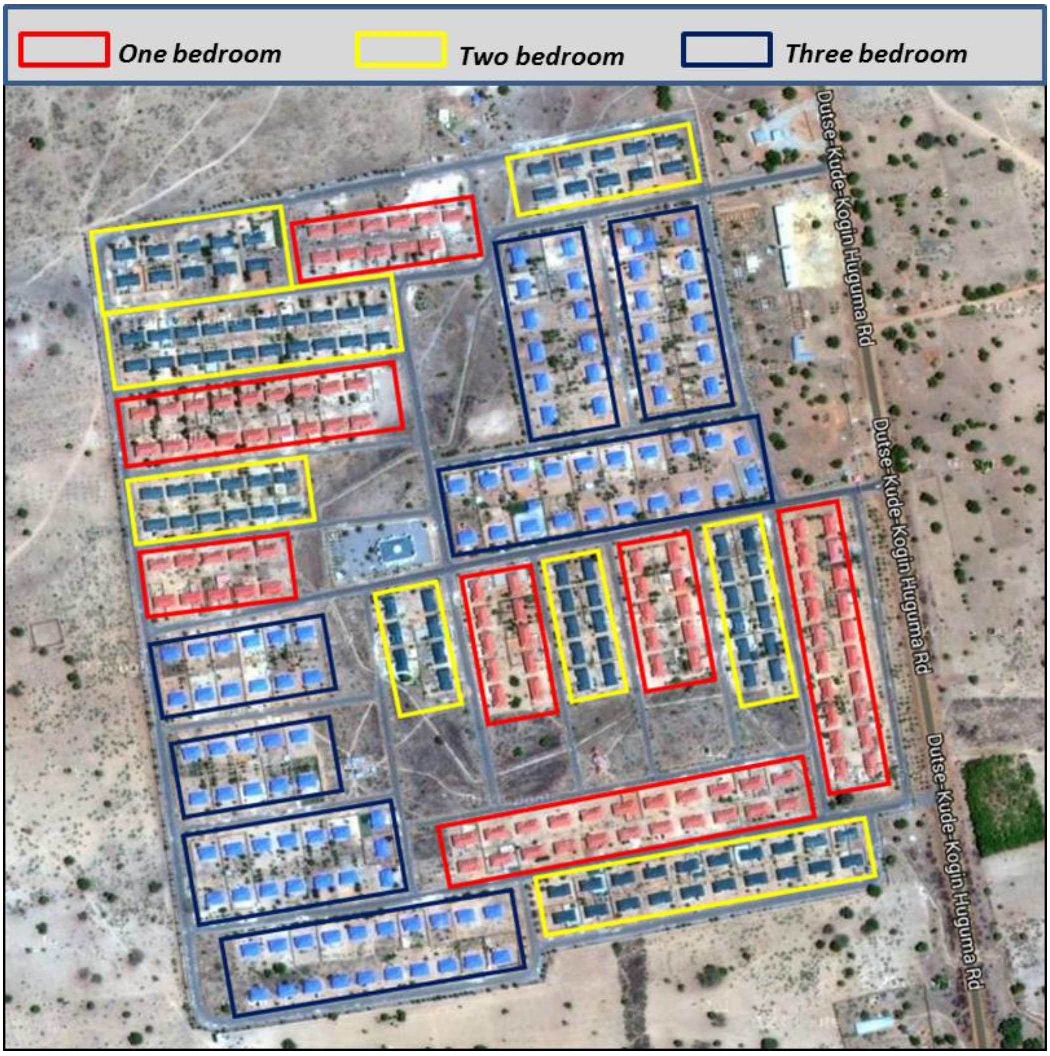



**Figure 4.3:** Distribution of households based on bedroom type

To carry out a survey where all household types are fairly represented given their type and location, it was deemed necessary to use stratified random sampling based on household type. Stratified random sampling helps guide against obtaining a biased sample which may likely over- or under-represent certain groups of the target population (Bowling, 2014). Table 4.1 shows the number of households for each of the strata selected. This was then used to calculate the sample size required for each strata as described in the following section.

**Table 4.1:** Number of households for each strata

| Strata | Number of households |
|---|---|
| **1 bedroom** | 202 |
| **2 bedroom** | 202 |
| **3 bedroom** | 101 |
| **Total** | **505** |

#### 4.6.4.1 Sample size

The Australian National Statistical Service calculator was used to determine the sample size for this survey. The calculations were carried out for a stratified random sampling with the strata being the household type as described earlier in this chapter. For each strata, a sample size was calculated. The parameters for the calculation are described below.

***Confidence level***

This is defined as the level of certainty with which the true population value is estimated. There are two default options in this calculator which are 95% and 99%. For this study, a confidence level of 95% was selected.

***Population Size***

This is the total number of persons or groups whose information is required for the survey. In this study, there are a total of 505 households.

***Proportion***

This specifies the expected proportion of the population to have the attributes being estimated from a survey. For this survey, a proportion of 90% was selected. The reason for this selection is based on the fact that all households in the study area are connected to the distribution mains. Also, the fact that the survey is an assessment of households' response to water supply service, it is safe to say that all households will at least have some form of response to the supply they receive.

***Confidence Interval***

This allows the desired level of accuracy of the estimate to be specified. The confidence interval value is expressed as a proportion and in this study, an accuracy of 5 percentage points of the result was chosen and hence, 0.05 was selected.

Table 4.2 below shows the values of the parameters for each of the strata (i.e. household type) that was used to calculate the sample size for the study.

**Table 4.2:** Parameters for the calculation sample size for stratified random sampling

| | **Strata** | | |
|---|---|---|---|
| | *1 bedroom* | *2 bedroom* | *3 bedroom* |
| **Confidence level** | 95 | 95 | 95 |
| **Population size** | 202 | 202 | 101 |
| **Proportion** | 0.90 | 0.90 | 0.90 |
| **Confidence interval** | 0.05 | 0.05 | 0.05 |
| **Standard error** | 0.02551 | 0.02551 | 0.02551 |
| **Relative standard error** | 2.83 | 2.83 | 2.83 |
| **Sample size** | **82** | **82** | **59** |

Despite having a target sample size for the study as shown above, a number of difficulties were encountered during implementation. For example, it was the researcher's target that survey starts by 7:30am and was expected to last till 4:30pm including weekends if possible. However due to the working nature of most of the household occupants, only a few households could be interviewed before they leave for work. This significantly reduced the number of potential participants available for interview during office hours. Moreover, when they came back from work, they were either too tired to too busy to participate in the survey. Also, because of the cultural and religious nature of this part of the country, it became difficult for female occupants that were left at home to be interviewed.

The aforementioned difficulties, coupled with time and financial limitations, prompted for the re-strategising of the sampling methodology earlier mentioned. A random walk sampling method was therefore adopted as an alternative to stratified random sampling. This is also widely used in household surveys and involves interviewers beginning the survey at a random point and walking along a specified path to select qualified households for interview. This technique is often employed even if valid sampling methods were used to select samples prior to the survey (United Nations Statistical Division, 2008). In this study therefore, researcher walks along each block within the study area to interview any available household. This was rather convenient as every household in the study area was a qualified household for interview.

To minimize the potential for bias, the researcher was however very careful in the selection of houses to interview. This was achieved by making sure each of the household types mentioned earlier in this chapter was fairly represented. An attempt was also made to ensure households from every block across the study area were included in the survey. Figure 4.4 shows the comparison of all the households and the distribution of interviewed households across the study area.

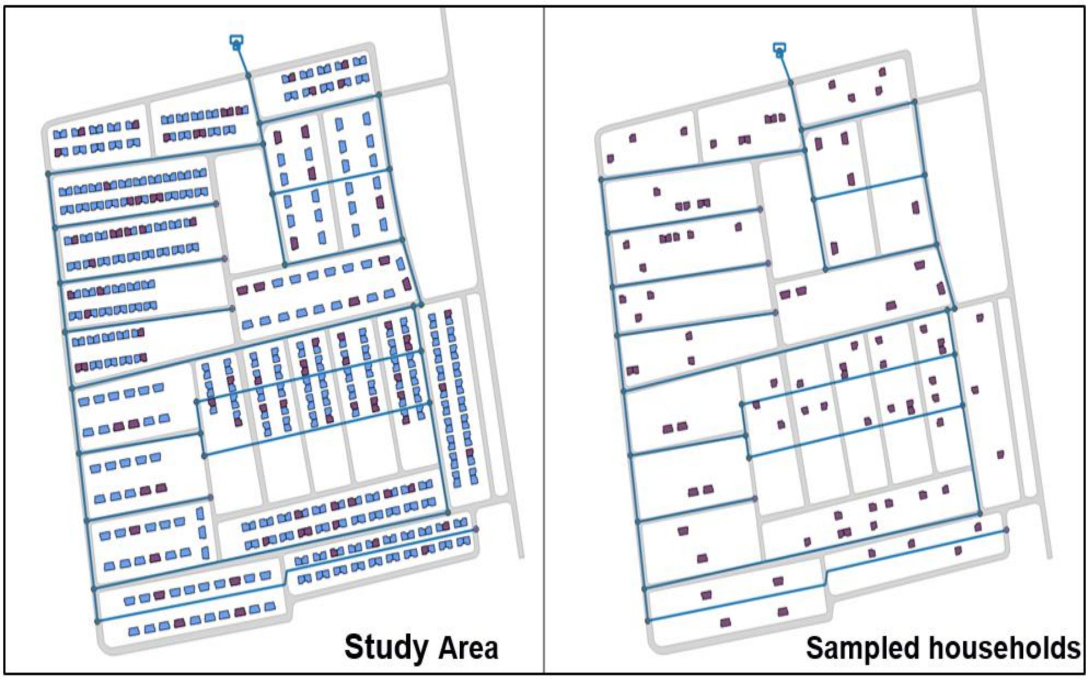



**Figure 4.4:** Distribution of households interviewed across the study area

At the end of the survey, a total of 90 households were interviewed. One participant opted out of the survey and data collected for that household was excluded from the analysis. Table 4.3 describes the difference between the calculated sample size based on stratified random sampling and the actual sample size based on random walk sampling. It also highlights the proportion of households covered against initial expected sample size.

**Table 4.3:** Comparison of sample size against interviewed households

| Strata | Total number of households | Sample size | Number interviewed | Percentage of sample size covered (%) | Percentage of total households covered (%) |
|---|---|---|---|---|---|
| **1 bedroom** | 202 | 82 | 37 | 45.1 | 18.3 |
| **2 bedroom** | 202 | 82 | 32 | 39.0 | 15.8 |
| **3 bedroom** | 101 | 59 | 20 | 33.9 | 19.8 |
| **Total** | **505** | **223** | **89** | | |

In general, the total number of households interviewed were 17.6% of the total number of households and 39.9% of the initially calculated sample size.

### 4.6.5 Data collection

The main survey instrument used in this study were questionnaires. Household demographics, water supply services and household water storage management options were the key themes within the questionnaire. These themes were adopted from the standard set of questions set by WHO/UNICEF on “Core Questions on Drinking Water and Sanitation for Household Surveys” (Organization and UNICEF, 2006) and modified to suit the research objectives. The questionnaire was piloted in a different area (Bayero University, Kano Staff Quarters) where water supply patterns and other physical features are similar to the case study area. The questionnaire was then modified before it was administered in the case study area. The sample of the survey questionnaire used in this study can be found in Appendix A.

### 4.6.6 Survey administration

The survey was carried out between June and August of 2016. The household survey questionnaires were administered to the participants face to face by the researcher. Information about the study was explained to the participant and informed consent was sought. Questions from the questionnaire were then asked by the researcher and responses from the participants were recorded as appropriate.

Administration of the questionnaire usually took between 40 – 90 minutes per household. After the questionnaire has been completed, the researcher asked for permission from the respondent to carry out measurements of water storage containers being used by the households. Where possible, pictures of these containers and, where present, electric pumps, were taken for referencing and analysis. In concluding each interview, the researcher gave each respondent the opportunity to further discuss issues that they think might be related to or beneficial to the study.

### 4.6.7 Data management and analysis

Analysis of the data collected from was carried out using Microsoft Excel and IBM SPSS 22. The responses from the questionnaires were coded and entered into SPSS database as variables. The process of coding involves allocating specific numbers to responses on the questionnaire. This is because SPSS only accepts data input in numeric form (Greasley, 2008). Cross tabulation analysis and frequencies were used to generate descriptive statistics on the data collected. This provides a general summary and information on the data being analysed (Greasley, 2008).

## 4.7 Key informant interviews

### 4.7.1 Introduction

Key informant interviews were carried out with the manager of the water utility company as well as the water supply technician of the study area. Key informant interviews involve interviewing persons who are expected to provide vital information and/or insight about the subject of study (Kumar, 1989). This is essential in that it offers a general picture of water supply situation in the study community and hence, identifying the water supply problems as viewed from the providers' standpoint. It is believed that the key informants mentioned above, being responsible for the supply of water to the study area, were in the best position to provide information on the problems and challenges with regards to water supply.

The interviews were semi structured where certain key themes were selected for guidance. These themes include: the job nature of the informant and his duties; description of how water is delivered to the study area; problems being faced when operating the network and the possible solutions to these problems.

To start the interview, the key informants were asked to introduce themselves and provide a basic description of their job. The flow of the interview determined the format through which the key themes were covered. In concluding, the key informants were then given the opportunity to further discuss or highlight important issues which were otherwise not discussed during the course of the interview.

### 4.7.2 Interview administration

The interviews were administered by the researcher through face to face interactions and responses were recorded on a digital sound recorder. The recordings were transcribed and key themes relevant to the survey were extracted and used for analysis where necessary.

Interview with the utility manager took place at the company's head office while that with the technician took place at the study area where the supply is being controlled. This was to ensure the participants were at their most comfortable locations. Both interview sessions lasted between 40-60 minutes.

Prior to the start of the interviews, the researcher explained the purpose of the study and sought informed voluntary consent from the participants. Furthermore, they were informed that they were free to withdraw from the interview at any time if they so wish.

It should be noted however, that the main reason for the interview was to get a general overview of the water supply system of the study area and the factors that are contributing to the level of service currently being delivered by the utility company. Data regarding hydraulics of the water distribution system was used for modelling and simulation purposes discussed later in this thesis. Information regarding duration of supply to households was used to compare with supply durations reported by households during the survey.

### 4.7.3 Water distribution network layout

Prior to the commencement of the household survey, the researcher, through the guidance from the technician, compiled the water distribution network (WDN) profile of the study area. All WDN features were identified and an inventory was recorded on the researcher's field notes. These features include; pipe routes, pipe sizes; pipe lengths; valve location; tank and pump specifications. The collection of such information was necessary as it was to be used for modelling and simulations which are an integral part of this thesis. More information on this is further discussed later in this thesis.

## 4.8 Challenges

Most of the household occupants were workers and leave for work between 7am and 10am. There was thus limited time available for the researcher to carry out the study given the timeframe available. Daily fieldwork hours were therefore limited to three to four hours (either before participants go to work or immediately after they come back; the latter being generally inconvenient as participants were often busy or tired). An attempt was made to interview participants late in the evening but very little progress was made. Furthermore, the survey was carried out during the rainy season and as a result, some days were lost due to heavy downpour.

During Key informant interviews, the researcher was told that each of the households had a water meter connected to the distribution mains. However, as the study started, it became clear that some of the households had no meters installed while others had either broken meters or they have been bypassed. Eventually, taking readings on meters was discarded as a data collection method. These limitations should therefore be taken into consideration when interpreting the findings of this study.

## 4.9 Results

This section describes the findings from the survey carried out. Descriptive statistics of the data collected are also presented. The findings from this survey will be used as appropriate in the subsequent chapters of this thesis.

### 4.9.1 Characteristics of respondents

The characteristics of the respondents from the study are summarized in Table 4.4. A total of 89 households took part in the survey, with samples across one *(n=37)*, two *(n=32)* and three *(n= 20)* bedroom houses.

**Table 4.4:** Characteristics of respondents

| **Sample characteristics** | *n* | Mean | Median | Standard deviation |
|---|---|---|---|---|
| **Total sample size** | 89 | | | |
| **Years of occupancy** | | 6.34 | 7 | 2.094 |
| **Average household size** | | 6.75 | 6 | 4.234 |
| **Age range** | | | | |
| **Under 5 months** | | 0.16 | 0 | 0.366 |
| **Under 5 years** | | 0.87 | 1 | 1.025 |
| **Between 5 and 16 years** | | 2.30 | 2 | 2.583 |
| **Adults** | | 3.43 | 3 | 2.094 |
| **Household type** | | | | |
| **One bedroom** | 37 | | | |
| **Two bedroom** | 32 | | | |
| **Three bedroom** | 20 | | | |

The average size of households was 6.75 persons, which was approximately equivalent to the average household size for Jigawa state (6.23 persons) and slightly higher than the North West region (5.3 persons). However, it was significantly higher than the national average of 3.8 persons per household (NBS, 2013). The analysis also showed that 16% (n=14) of the households had at least one child under five months while 52% (n=47) had at least one child under five years. There was a high percentage (70%, n=63) of households with at least one child between the age of 5 and 16 years.

### 4.9.2 Existing water supply

The Jigawa State Water Board is the State Water Agency (SWA) responsible for the provision of water to the study area through a water distribution network consisting of PVC pipes that range between 50mm to 150 mm. The network is being fed by a 270 cubic metre tank located at a base station within the residential estate. A total of 6 boreholes supply water to the tank which then feeds the estate through a pump station. As at time of carrying out this survey however, only two of the boreholes were operational. Information gathered regarding the physical components and the mode of operation of the distribution network is further discussed in Chapter 5.

Households reported an average supply of 8.6 hours per day where 16 households (18%) reported having less than 1 hour of supply per day and 4 households (4.5%) reported having 24 hours of supply (Figure 4.5).

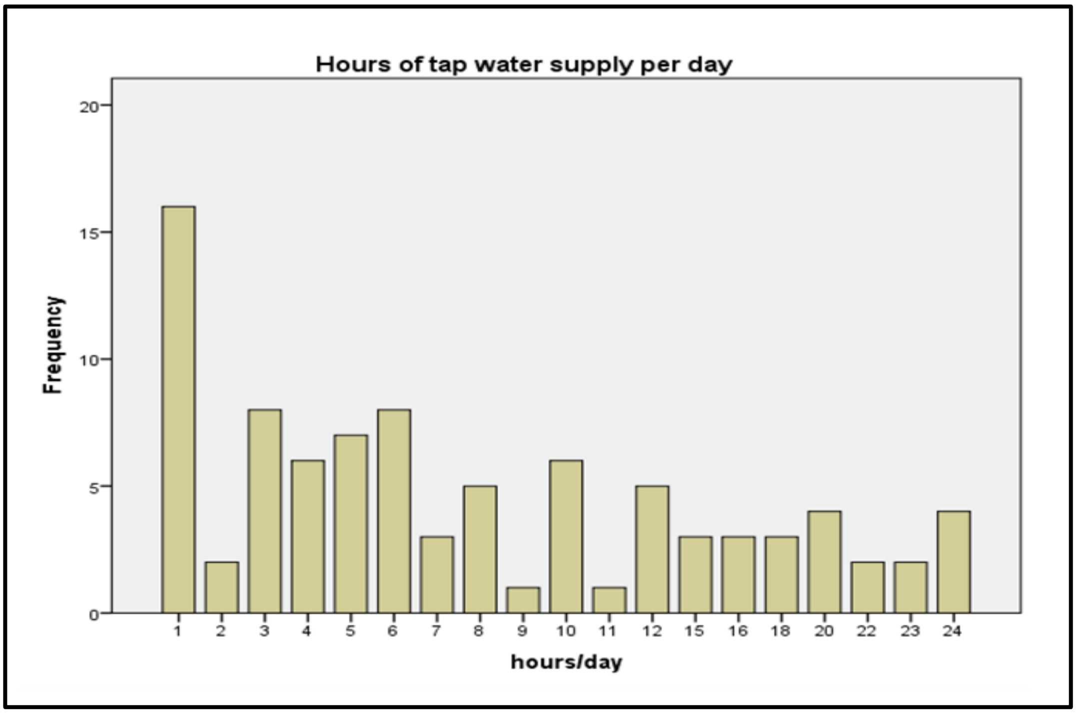



**Figure 4.5:** Hours of tap supply for households

This is however, contrary to the hours of supply reported by the state water agency (16 hours) and well below the 15 hours average reported for the state (Macheve et al., 2015). The study revealed that all households had piped water connections from the distribution mains with majority (82%) of them having tap water as their main source of water. However, 9% of the respondents relied on buying an average of 270 litres each from water vendors daily while about 7% resorted to building boreholes and shallow wells as their main source of water. Table 4.5 gives a descriptive statistics of households' main sources of water.

**Table 4.5:** Main source of water

| | *n* | *Percent (%)* |
|---|---|---|
| **Tap in house/yard** | 73 | 82.0 |
| **Protected well/Borehole in Yard** | 6 | 6.7 |
| **Shallow/Open well in yard** | 1 | 1.1 |
| **Borehole outside yard** | 1 | 1.1 |
| **Water vendor delivery to house** | 8 | 9.0 |
| **Total** | 89 | 100.0 |

Some households report having other sources of water as presented in Table 4.6. About one third (28.1%) of the respondents report having other alternative sources of water with 12 households (13.5%) having tap as their second option for source of water.

**Table 4.6:** Alternative source of water

| | *n* | *Percent (%)* |
|---|---|---|
| **Tap in house/yard** | 12 | 13.5 |
| **Protected well/Borehole in Yard** | 2 | 2.2 |
| **Shallow/Open well outside yard** | 1 | 1.1 |
| **Water vendor delivery to house** | 8 | 9.0 |
| **other** | 2 | 2.2 |
| **Total** | 25 | 28.1 |

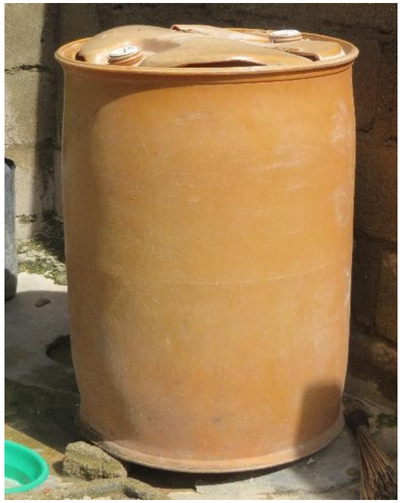
Some households (9%) report purchasing from water vendors as an alternative to their main source of water while a few (3.3%) use wells as alternatives.

### 4.9.3 Storage

The different types of storage containers identified during the survey were classified into categories as described in Table 4.7. The storage containers were all located within the compound of the household but could be located either inside or outside of the main building; this mostly depended on the size of the container.

**Table 4.7:** Types of storage found

| Type | Description | Volume range | Location | Image |
|---|---|---|---|---|
| **Buckets and other smaller containers** | Usually made of plastic or aluminium. Some are used paint buckets.<br>Also included in this category are locally made clay pots. | Usually between 15 to 80 litres | Mostly indoors in toilets and kitchens but can also be found outside usually covered with a lid. |  |
| **Jerry Can** | Mostly made of plastic. Some are purposely made for water storage. Others are used cooking oil jerry cans washed and used for storage. | Volume ranges between 10 and 80 litres | Smaller ones usually found indoors in toilets and kitchens while larger ones are usually found outside. |  |

| | | | | |
|---|---|---|---|---|
| **Drums** | Made of plastic or metal. Some are old oil drums with the top being removed. | Usually between 80 to 300 litres | Found both inside and outside. |  |

| | | | | |
|---|---|---|---|---|
| **Plastic Tanks** | Usually large storage containers made of plastic. These are usually placed on the ground (surface tank), overhead on a tower or on a rooftop (Overhead tank) or buried in the ground (Underground tank). | Mostly between 500 and 2000 litres per tank | All located outside in the yard. |  |
| **Concrete tanks/reservoirs** | Locally constructed concrete reservoirs usually built underground. | Usually very large but volume mostly depends on owner's requirements | Always located outside in the compound. |  |

The study found that almost all (93%) of the respondents have adopted some form of water storage measure using large outdoor storage tanks (46%) and/or some form of smaller household storage container (83%). Of those households that have outdoor storage tanks, it was found that the average capacity of these tanks (which comprises of underground, surface and overhead tanks) was around 2,500 litres while the average for other smaller household containers was 250 litres per household.

According to the water supply technician, it is illegal for households to use underground tanks but in the study, it was found that 24% of those household with outdoor storage tanks had an underground tank. One particular household, upon verification by inspection, had an underground reservoir with a capacity of 16,000 litres.

Asked whether they would still store water if supply was continuous and reliably available, 40% of respondents said they would while 60% said they would not as there will be no need to store any water.

Figure 4.6 shows the relationship between hours of supply received by households and volume of their storage containers using Pearson product-moment correlation coefficient.

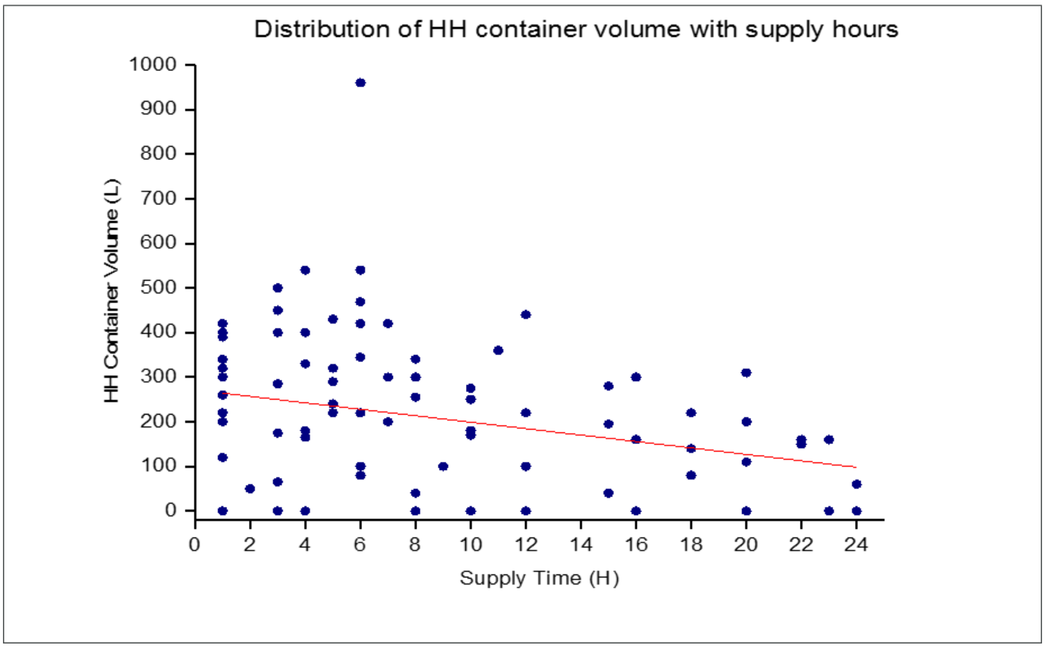



**Figure 4.6:** Distribution of household container volume with supply hours

The results show that there was a medium negative correlation between the two variables, $r = -0.337$, $n = 89$, $p < 0.01$, where lower hours supply was found to be associated with higher volumes of storage containers.

### 4.9.4 Household water treatment

Throughout the survey, observations of all storage containers have revealed that none of the households interviewed had any form of household treatment mechanisms like filters or purifiers. However, upon further discussion with respondents, it was discovered that the quality of water received was good enough for most of the house chores. Occasionally however, some respondents have reported boiling as means of treating drinking water.

### 4.9.5 Electric pumps

In addition to storage, and the desire to store as much water as possible during supply hours, some households employ the use of electric pumps (Figure 4.7).

In some cases, this is to pull water from the network while others use it only to pump water to their overhead tanks.


**Figure 4.7:** An example of electric booster pump used by some households

The study found that more than one-third (36%) of the total respondents had electric pumps, of which 68% have the pump directly connected to the distribution mains. In addition, Figure 4.8 shows that with regards to hours of supply, the 36% of households that reported having 0-6 hours of supply per day had electric pumps installed in their households.

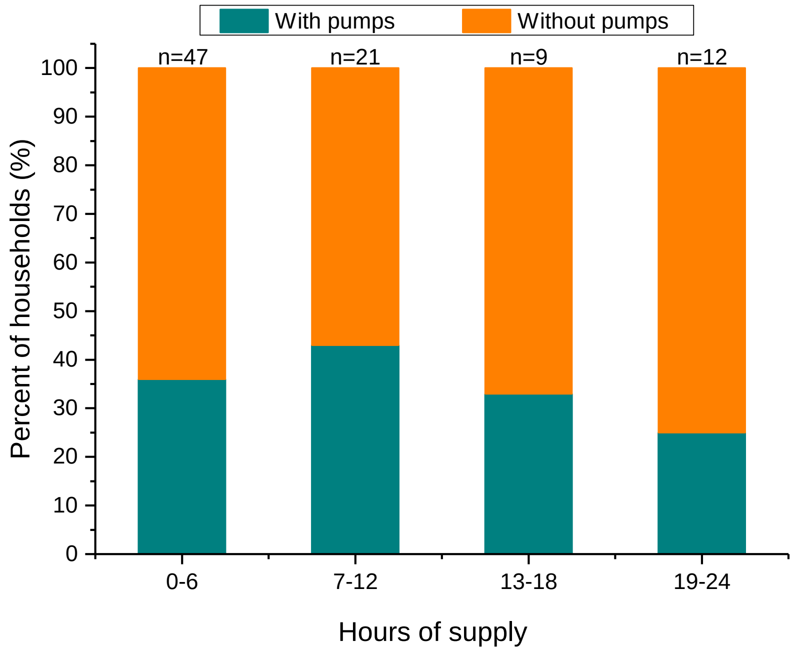



**Figure 4.8:** Households with pumps based on number of hours of supply

Similarly, about 43% of households with 7-12 of supply and up to 33% of those who reported 13-18 hours of supply were found to be using electric pumps. However only a quarter (25%) of households with between 19 to 24 hours of supply were found to have installed an electric pump.

Taking household type into consideration, Figure 4.9 shows that for one- and two-bedroom households, approximately 30% of the respondents each had electric pumps. However, more than half (55%) of the three-bedroom houses had electric pumps.

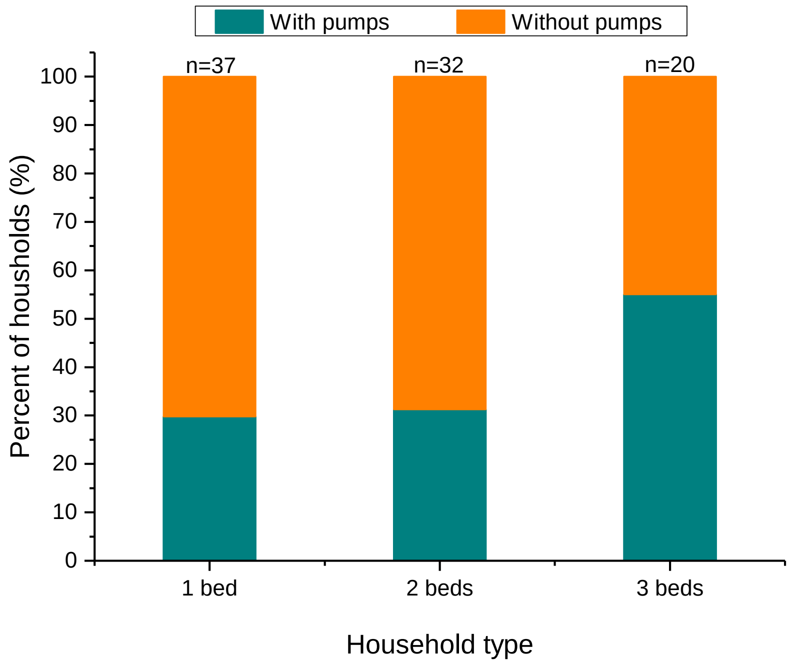



**Figure 4.9:** Percentage of households with pumps based on household type

### 4.9.6 User preference

#### 4.9.6.1 Level of service

In trying to improve the levels of service being provided by systems which are usually intermittent, a number of options are usually considered. The first option, which is the most desired, is to provide continuous supply with sufficient pressure enough to satisfy consumer demand at any given time. However, when resources are limited, or the capacity of the water source and/or the distribution system infrastructure is insufficient, the following options may be considered:

- To provide a continuous supply but with reduced pressure. This means that users will have continuous supply, but it might take them a longer time to collect water.

– To provide intermittent supply but with reasonably higher pressure. With this, users will still get intermittent supply but whenever the supply is switched on there is sufficient pressure to allow users collect enough water before supply is switched off again.

In light of the above, participants in this study were asked which they would prefer between having a continuous supply but with lower pressure or having an intermittent supply but with higher pressure. The study found that although there is strong inequality in the supply duration across the study area, more than half (58%) of the total respondents said they would prefer continuous supply but with lower pressure while the remaining (42%) preferred intermittent supply as long as the pressure is sufficiently high.

Figures 4.10 and 4.11 describes the preference of households based on hours of supply they receive and also based on type of household. The results show that 53%, 57% and 56% of the households with 0-6, 7-12 and 13-18 hours respectively, prefer having continuous supply with lower pressure, while the remaining said they would prefer intermittent supply as long as the pressure remains high.

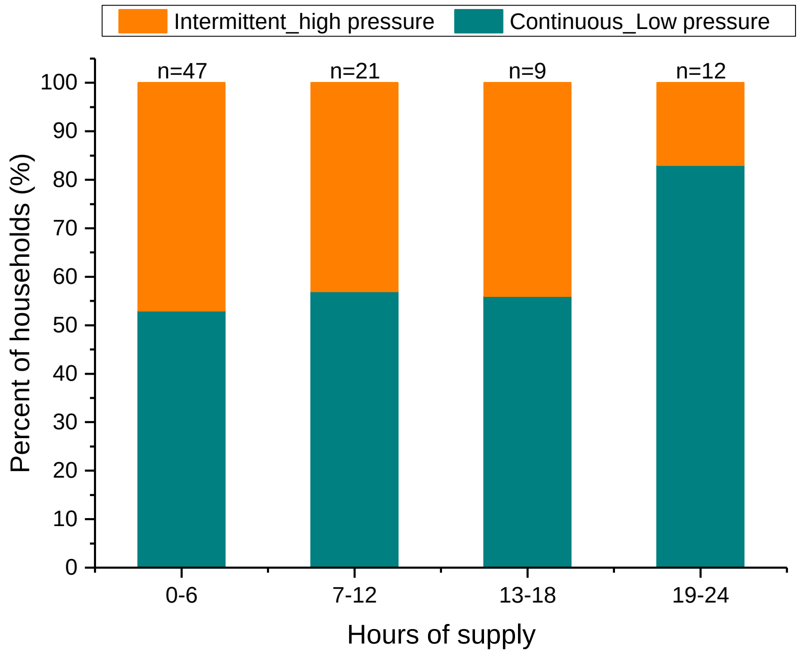



**Figure 4.10:** Supply preference of respondents based on hours of supply

However, households reporting up to 19-24 hours of supply were found to have significantly higher percentage with up to 83% who preferred having continuous supply but with lower pressure.

When analysed based on household type, 59%, 53% and 65% of households with one, two and three bedrooms respectively, also preferred having a supply which is continuous but with low pressure.

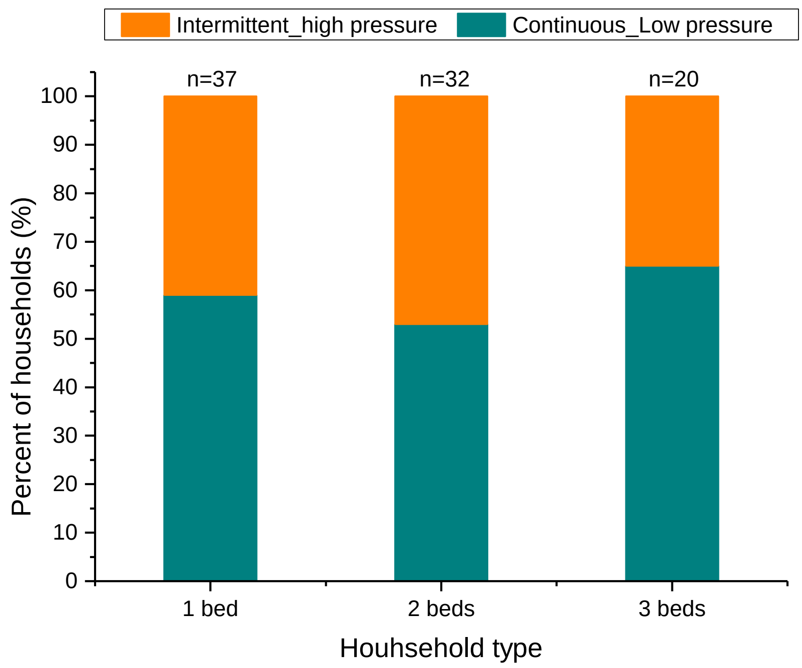



**Figure 4.11:** Supply preference of respondents based on household type

This shows that across all household type, majority of the respondents would prefer continuous supply with low pressure as against an intermittent supply with high pressure. However, it is worth noting that a certain number of participants would accept IWS as long as it is reliable.

#### 4.9.6.2 User satisfaction

This study also found that majority (76%) of the respondents say they close their taps when supply stops while 16% say they leave their taps open. The reason for leaving the tap open may be to enable them collect water either if they are not around or if they might be sleeping when the supply resumes. This however has the potential to cause water wastages as have been reported in several studies (Batish, 2003, Kumar, 1998, Kumar, 1989). Despite the discomfort of having to store water coupled with an average of 8.6 hours of supply, about 60% of the respondents said they were satisfied with the type of supply they receive.

## 4.10 Conclusions

Most respondents in the study reported intermittent water supply was common, with supply lasting an average 8.6 hours per day. This is contrary to the state water agency's claim of providing at least 16 hours per day. This shows that the total bulk water from the tank may not be enough to cater for the needs of the study community, or user behaviour is greatly influencing the quantity and supply time provided. Because majority of the households rely on tap water as their main source of water, the intermittency in supply has forced them to adopt certain coping strategies, the most common of which is having some form of storage containers to store water for use when there is no supply. Most households with smaller containers within the household have been found to store an average of 250, while an average of 2500 litres was found in households that have outdoor storage tanks. Households that purchase water as their main source of water were found to be buying an average of 270 litres per day.

Other strategies adopted by households is having an electric pump installed and connected to the distribution mains to increase their supply. This this might consequently have adverse effects on the network. Even though 24 hours supply is the most preferred option by households, intermittent water supply will still be accepted by households if the pressure will be enough to allow households store water for their daily use.

The presence of intermittent water supply forces users to behave in various ways in order to meet their demands. This survey has shown that these behaviours vary with individual households. The findings from the survey have highlighted the significance of households' coping behaviour in order to achieve a certain level of autonomy from a rather deficient water supply system. The challenge here might be the ability of predicting how and when these behaviours are carried out. This shows the level of complexity that is attributed to the operation of IWS. Furthermore, these uncertainties in coping mechanisms makes it a challenge for modellers in simulating the operation of an intermittent water supply system.

Further work is therefore required to examine how these individual coping responses affect other households and how they affect the level of service of the water distribution system. The study should focus on the variation of pressure in the water distribution system within the community and to understand how it might affect individual households or sections within the distribution network.

# Chapter 5: Characterisation and Model Development of the Case Study Water Distribution System

## 5.1 Introduction

This chapter is divided into three sections. The first section describes the background of water distribution systems modelling and the general concepts for computer simulation of such systems. The basic system elements and governing equations are also discussed.

The second section describes the WDN of the case study area based on data collected from the fieldwork and presents some initial capacity performance assessment results.

Finally, the third section describes the development of a hydraulic model of the WDN for the case study based on physical information of the system obtained during the field work. The hydraulic modelling software selected for the simulations is also briefly discussed together with assumptions considered in the development.

## 5.2 Modelling and simulation of water distribution networks

### 5.2.1 Introduction

The aim of the simulation is to create a computational representation of the WDN to be able to assess the spatial and transient performance of the network in terms of flow and pressure. The modelling tool enables solution of underpinning mathematical equations that describe the flow on the network with time.

Simulation is an important tool for understanding flows and pressures in a WDN under different conditions. The assessment of water distribution system response under specific operational conditions (e.g. valve closing and opening, different reservoir head, etc.) or different water demand profiles can be used to explore design and control strategies before applying the action to the actual water network.

The following simulation methods can be distinguished: (i) Transient simulation, (ii) steady-state simulation and (iii) extended-period simulation (EPS). The most accurate simulation of water distribution system is obtained using transient simulation; this is because it considers unsteady flow conditions in its natural form while incorporating transient analysis. However, due to its complex nature, the method has not yet been fully adopted by practitioners (Xing and Sela, 2020), and is mainly limited to specific applications such as simulation of pipe segments (Gong et al., 2013, Wang et al., 2002) and small theoretical networks with simple topologies (Capponi et al., 2017, Liggett and Chen, 1994). Steady-state simulation considers demands and pressures at every node and assume that the flows throughout the system network do not vary over time. However, in practical situations these parameters vary with time, so a steady-state simulation is only appropriate for systems where the demands and sources can be assumed to be constant. Thus, extended-period simulation (EPS) is used as a hybrid approach for evaluating the performance of WDS over length of time. This type of simulation considers variations in aspects such as reservoir or tank head and the demands at supply nodes at discrete intervals of time. However, the system is assumed to be at steady state at each time interval which reduces the computational demand compared to a fully transient model. Steady state and EPS are further discussed later in this chapter.

Simulation of a water distribution system is not easy, as solutions to the governing equations can only be obtained analytically for very small and simple networks. The flow continuity equation can easily be applied at all nodes for a tree-shaped network to obtain a solution, but in practice water distribution networks are not always tree-shaped (see figure 5.1). Analysis of looped water networks offers more difficulties, as the model has to consider the flow through the loops rather than just simple division into branches.

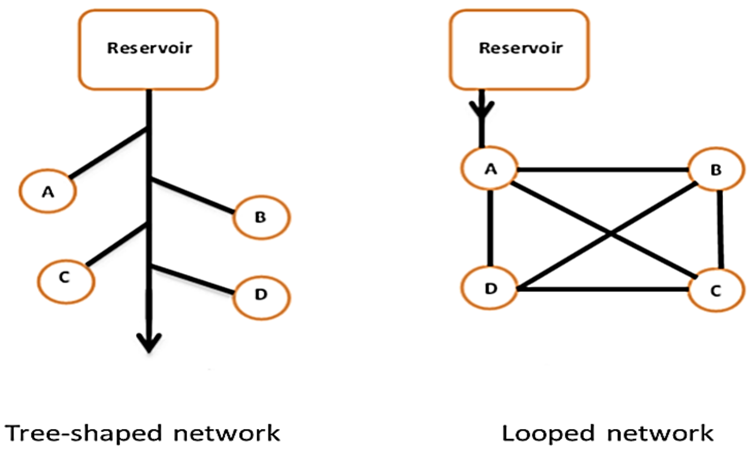



**Figure 5.1:** Example of a tree-shaped and looped WDN topology

Solutions require an iterative approach and a number of methods were proposed over the last decades (Ormsbee, 2008, Wood and Rayes, 1981), including: (i) the linear theory method (Wood and Charles, 1972); (ii) Hardy Cross method (Cross, 1936); (iii) the linear graph theory method (Kesavan and Chandrashekar, 1972); (iv) the Newton-Raphson method (Shamir and Howard, 1968),; (v) the global gradient method (Todini and Pilati, 1988) and (vi) an approach involving optimization methods (Collins et al., 1978). The most recognized and utilized methods are discussed in this section.

### 5.2.2 Hardy Cross method

Hardy Cross method was the earliest technique for the analysis of water network, the technique was proposed by Cross in 1936. The method is an adaption of Newton's method. The method was developed before the advent of computers, leading to manual analysis of pipe network. To illustrate the iterative approach of solving loop equations in pipe network systems, the Hardy Cross method is presented.

If the flow rate in each pipe is represented as $\hat{q}$ and Δq is taken to be the error in this representation, then actual flow rate q may be defined as follows:

$$q = \hat{q} + \Delta q. \tag{5.1}$$

After series of mathematical transformations and substitutions (see Cross (1936) for more in-depth details), the above equation forms the basis of the Hardy Cross method and can be written as

$$\Delta q_p = -\frac{\sum_{m=1}^{NP(p)} R_m q_m^{\beta}}{\sum_{m=1}^{NP(p)} \beta R_m |q_m|^{\beta-1}}, \tag{5.2}$$

where $NP(p)$ is the number of pipes in a given loop $p$, $R_m$ is the coefficient of head-loss in pipe $m$ (in loop $p$), $q_m$ is the flow estimate in pipe $m$. $\Delta q_p$ is the flow correction for the pipes in loop $p$.

Hardy Cross technique tends to estimate the conditions of flow throughout the system network to fulfill the law of flow continuity at every node. As initial approximation may not fulfill the continuity law due to head loss, discharge corrections are applied for every loop to arrive at zero head loss around the loop. This process is repeated iteratively until the corrections values are less than a quantified value. Computationally, the method is more rigorous than other techniques and it presents a good initial flow estimate for its convergence (Mays, 1999).

### 5.2.3 Linear theory method

In 1972, two scientists, Wood and Charles came up with another technique in which all the equations for every path or loop are analyzed simultaneously to find the rate of flow in each pipe. In this technique, the linearized equations for head loss form a set of linear equations, subsequently; these sets of linear equations are then solved iteratively for the unknown flow values. At each iteration, the outright differences between succeeding flow estimates are calculated and matched to a convergence criterion; this means that if there is a significant differences between the successive flows and the convergence criterion the process will be run again for iteration (Mays, 1999).

Due to combination of conservation of energy equations and conservation of mass in this method (linear theory), the nodes initial flow balance is not necessary, but the linear theory method can oscillate near exact solution a times (Wood and Charles, 1972).

### 5.2.4 Gradient method

In 1988, Todini and Pilati proposed a gradient method algorithm that is widely used nowadays. The method takes into consideration both pipe flows and nodal heads to solve simultaneously the energy equation and the conservation of mass (Todini and Pilati, 1988). Taylor series expansion was first used to linearize the nonlinear equations to produce the linear equations of the overall system:

$$\begin{bmatrix} A_{11} & A_{12} \\ A_{21} & 0 \end{bmatrix} \begin{bmatrix} q \\ h \end{bmatrix} = \begin{bmatrix} -A_{10}h_0 \\ d \end{bmatrix}, \tag{5.3}$$

where $A_{11}$, $A_{12}$, $A_{10}$, $d$ and $h_0$ are the diagonal matrix, unknown head nodes incidence matrix, fixed head nodes incidence matrix, nodal demands and fixed nodal head, respectively.

Differentiating both sides of the above equation (gradient method) will lead to Newton-Raphson iterative technique to be obtained.

$$\begin{bmatrix} \beta A_{11} & A_{12} \\ A_{21} & 0 \end{bmatrix} \begin{bmatrix} dq \\ dh \end{bmatrix} = \begin{bmatrix} dE \\ dd \end{bmatrix} \tag{5.4}$$

and where

$$dE = A_{11} q^k + A_{12} h^k + A_{10} h_0 \tag{5.5}$$

$$dd = A_{21} q^k - d \tag{5.6}$$

are the residuals to be iteratively evaluated for flows $q_k$ and heads $h_k$ at iteration $k$; and $\beta A_{11}$ is the diagonal matrix of the exponents of the pipe equations.

Updates to $q_{k+1}=q_k+dq$ and $h_{k+1} = h_k+dh$ will continue subsequently until convergence is attained; that is residual $dd$ and $dE$ are reduced to zero. Even though, larger set of equations are required in gradient algorithm compared to linear theory or Hardy Cross methods, it has shown to be computationally efficient and robust (Mays, 1999, Todini, 2008). His is the governing equation behind the operation of EPANET 2 software (Rossman, 2000) which will be discussed later in this chapter.

### 5.2.5 Steady State Simulation

Steady-state simulations compute the state of the network at a fixed point in time. This involves computing pressures, flows, valve attributes and pump characteristics of the distribution system. Steady state analysis is sometimes described as way of obtaining a “snapshot” representation of a system. Simulations are usually carried out during extreme conditions such as times of peak demand, during use for fire protection and more so during failure events of any of the system component (Walski et al., 2007, AWWA, 2018). These are times when system demands and pressures are at their lowest and highest points. If a system can operate satisfactorily under extreme conditions, then it can safely operate under all other conditions.

Steady-state analysis can be used to evaluate several hydraulic problems in water distribution systems as well as carrying out performance analysis of the system using different operating scenarios (Kapelan et al., 2005, Osman et al., 2016, Zecchin et al., 2012). Some common analysis using steady-state scenarios are maximum hour, minimum hour, average day, maximum day plus fire flow and emergency condition analysis. These scenarios are also coupled with tank levels at their maximum and minimum points.

#### 5.2.5.1 Maximum Hour Demand Analysis

Maximum hour (sometimes referred to as peak hour) demand is that hour of the day where the system demand is at its highest (AWWA, 2018). Distribution systems are usually designed to meet peak demands with considerations given to both production and storage capacity of the system. Maximum hour demand analysis is therefore used to assess the capability of all components of the distribution system to withstand these extreme conditions and effectively sustain adequate residual pressure.

Running maximum hour demand analysis involves setting the model to run on peak factors of maximum day demands. In systems being supplied by a tank, it requires setting the tank water level at the lowest recorded value. Normally, for standard distribution systems operating 24 hour supply, the lowest possible value is assumed to be when the tank is half-full (AWWA, 2012). For systems whose storage tank drains almost empty however, it may be useful to adopt even lower tank levels as this would provide better understanding of the system operation at very low tank levels.

Maximum hour demand analysis helps in comparing pressure values during worst case situations for various operation scenarios and hence, can be used to suggest areas of possible improvements. When models predict pressure values outside design criteria or acceptable limits, further improvements on the system can then be suggested and analyzed.

#### 5.2.5.2 Minimum Hour Demand Analysis

Minimum demand condition is the point at which water use during the day is at its minimum. Usually, this occurs at the early hours of the morning when most users are asleep (AWWA, 2018). During intermittent supply, minimum demand is assumed to be at the later hours of supply when most users have filled their storage containers before supply is switched off (Kumpel and Nelson, 2013, Vairavamoorthy et al., 2007a).

Normally, simulations of minimum hour are used to determine the maximum pressure that the system will have to experience during the day as when there is low consumption pressure is at its highest. This is because very high pressures are known to cause damage to some of the components within the distribution system. Results from minimum hour demand simulations help in assessing the systems vulnerability to high pressure conditions by indicating points where interventions are needed.

Running minimum hour demand simulations involve setting the model to run on minimum consumption while initial tank levels are set at the highest value. Normally, this is when the tank is full. However, with uncertainties in the mode of operation of most systems providing intermittent water supply especially gravity driven systems, it would be essential to assess networks at different initial tank levels. Different multiplying factors should also be used to check the sensitivity of the system to change in demand.

### 5.2.6 Extended period simulation

Extended period simulation (EPS) is another method used in modelling WDSs through a series of steady-state simulations considered at regular intervals and executed over a specified period of time. Unlike steady-state analysis whose functionality is more useful in the design and sizing of supply facilities and pipelines, EPS provides a more robust and in-depth information about the characteristics and mode of operation of water distribution systems. In addition it provides information on response of a system with change in demands over time (Walski et al., 2007). The information produced by EPS enables modellers to appropriately determine characteristics of system components fluctuations in tank and reservoir levels as well as their sizes, sizing of booster pumps and helps in aiding the improvement of distribution systems. In addition, EPS simulation helps modellers decide the best location and possible sizes of storage and pumping facilities during both design and improvement stages. Only models with EPS capabilities are able to carry out simulations of water quality and energy analysis. Models of EPS can easily be generated for steady-state models.

Except for modelling water quality simulations, EPS simulations are usually run through 24-hour period, but this depends on the purpose for which it is being run. Usually, these periods are divided into smaller time periods of typically 1 hour. Water quality models needs much longer time periods to determine stable water quality results (AWWA, 2018).

In addition to data used in steady state simulations, EPS requires input to determine how certain time dependent outputs vary over time. These include operation of pumps, valves and reservoir or tank levels. EPS is therefore a very useful tool in selecting various operational scenarios of a distribution system to assess the resulting effects on the performance of the system.

### 5.2.7 Baseline demands

One of the initial steps in modelling WDNs is the determination and allocation of baseline demands, where different peak factors and demand multipliers can be employed. Typically, baseline demands incorporate both consumer demands and non-revenue water.

Existing data from utilities is usually the first source for obtaining demand information for a specific area. Other sources include data from previous studies and models which, if available, greatly reduces the amount of time that would usually be spent determining the demands. It is very common however, to have utilities with no such information or the records available may be outdated. In such instances, certain operational records may be used to gain insight into the demand characteristics of a distribution system (Walski et al., 2007). Some of these records include:

- Flow information, which may include the production rate of a well or a utility,
- Volumetric information, which may include the amount of water withdrawn by the user, and
- Hydraulic grade information, which may include the variation of water level for a tank.

The above information is usually obtained in varying formats which may need to be converted prior to being used. The tank level data for example, can be converted to volumes using physical dimensions of the tank. These volumes can be directly converted to flow rates when the tank level variation over time is incorporated into the data.

#### 5.2.7.1 Demand Estimation

There are two basic methods used in the estimation of baseline demands prior to loading onto the model. These are the *top-down* approach and the *bottom-up* approach (Walski et al., 2007) and are governed by the general concept of mass balance. These approaches are sometimes called *estimated consumption* method and *actual consumption* method (Cesario, 1995) as both methods do involve estimation at certain levels.

Determination of demand using the top-down approach involves using production and consumer data and disaggregating it down to the consumers. This, for example, may be achieved by dividing the output from a source over time and dividing it by the number of consumption points. This can then be used to determine the nodal demands.

On the other hand, the bottom-up method is the opposite, where customer consumption records can be summed up to determine the nodal demands. In some instances where meter readings are not available, the per capita demand, as set by utilities or national standards, can be used as consumption records.

#### 5.2.7.2 Mass balance technique

Mass balance techniques are useful methods used to determine the variation of demands over a specific time period. In a typical system of WDN, mass balance shows that the amount of water going into the system (or change in storage) should be the same as the amount that comes out of the system. This can be expressed by the following equation (Walski et al., 2007):

$$Q_{demand} = Q_{inflow} - Q_{outflow} + \Delta V_{storage}/\Delta t, \quad (5.7)$$

where $Q_{demand}$ = average rate of demand ($m^3$/s, litres/s)

$Q_{inflow}$ = average rate of production ($m^3$/s, litres/s)

$Q_{outflow}$ = average outflow rate ($m^3$/s, litres/s)

$\Delta V_{storage}$ = change in storage in the system ($m^3$, litres)

$\Delta t$ = time between volume measurements (sec)

It should be noted that the demand and production rates in equation (5.1) are representative of the average flows through the time period. However, the change in storage ($\Delta V_{storage}$) is obtained by calculating the difference between tank volumes at the beginning and end of the time period. This can be represented by the equation:

$$\Delta V_{storage} = \sum_i (V_{i,t+\Delta t} - V_{i,t}), \quad (5.8)$$

where $V_{i,t+\Delta t}$ = storage volume of tank $i$ at time $t + \Delta t$ ($m^3$, litres)

$V_{i,t}$ = storage volume of tank $i$ at time $t$ ($m^3$, litres)

For tanks with vertical sides (e.g. standing cylindrical tanks, square and rectangular tanks), change in water level in the tank can be used to determine the change in storage using Equation (5.3) below:

$$\Delta V_{storage} = \sum_i (H_{i,t+\Delta t} - H_{i,t}) A_{i,t} \tag{5.9}$$

Where $H_{i,t+\Delta t}$ = level of water for tank $i$ at beginning of time step $t + \Delta t$ (m)

$H_{i,t}$ = level of water for tank $i$ at beginning of time step $t$ (m)

$A_{i,t}$ = surface area of tank $i$ through time step $t$ ($m^2$)

Gauges and other special water level measuring devices are used to obtain the values for the variation of water level in a tank.

### 5.2.8 Multiplying factor

Multiplying factors, sometimes called peak factors or multiplicative factors, are numbers that may be applied to demand values of a whole system or a number of nodes within a system (Cesario, 1995). A multiplying factor, which may also be defined as the discharge ratio, can be applied to various demand situations to determine boundary conditions on consumption (Walski et al., 2007). Equation 5.9 can be used for example, to calculate the multiplying factor applied to the average day demand in order to obtain maximum day demands.

$$MF = Q_{max}/Q_{avg}, \tag{5.10}$$

where $MF$ = multiplying factor between maximum day and average day demands

$Q_{max}$ = maximum day demands ($m^3$/s, litres/s)

$Q_{avg}$ = average day demands ($m^3$/s, litres/s)

Multiplying factors are important in modelling in that they can be used to predict how a distribution system would perform under stressful conditions (AWWA, 2018). Normally, these conditions, which are explained later in this chapter, include the peak hour and maximum day conditions.

### 5.2.9 Demand patterns and diurnal curves

During steady state analysis, demands are assigned to a hydraulic model as fixed demands. This means that they represent "snapshot" of a particular demand condition. However, water demands are not fixed and therefore vary with time. The representation of this variations in the model hence requires a diurnal curve.

A diurnal curve (sometimes called diurnal patterns) is a dimensionless profile that describes how demands vary with respect to the average demand over a 24-hour supply period (AWWA, 2012). Figure 5.2 gives an example of a diurnal curve over a 24-hour period. The value of the actual demand at a particular hour is calculated by multiplying the average daily demand (100% in the case of Figure 5.2) by the diurnal profile value (sometimes called "multiplier") of that particular hour.

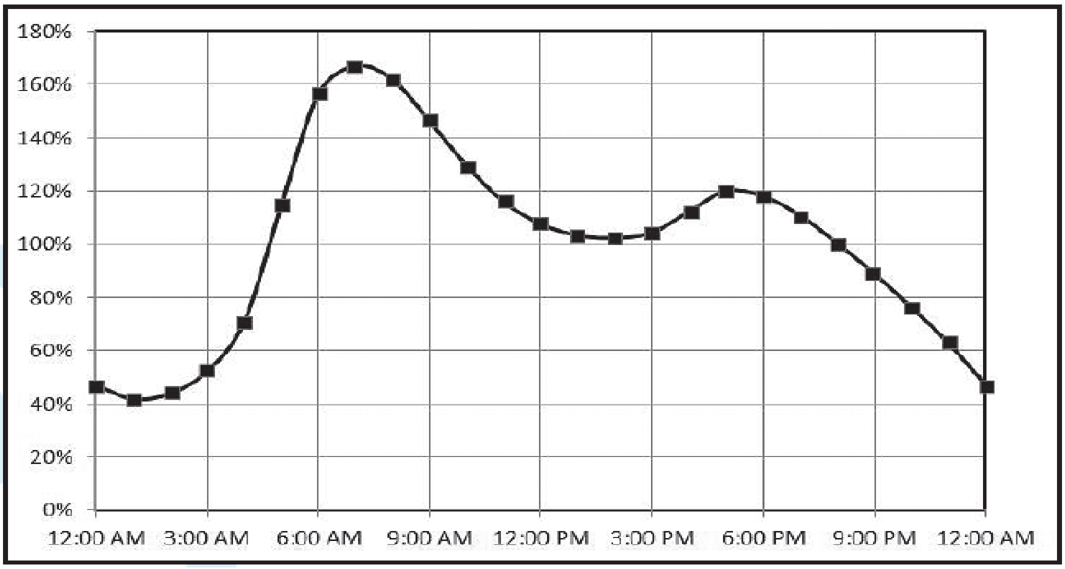



**Figure 5.2**: Typical diurnal pattern for water demand. Source: AWWA (2012)

The multiplier can be expressed in a fraction or a percentage (Y-axis) while the time (X-axis) can be varied depending on the purpose for which the model is being used for.

In potable water distribution systems, diurnal patterns vary depending on how, and for what reason water is being used by the consumer. The diurnal curve for a residential area will obviously be different from that of a factory or a restaurant. Figure 5.3 shows how diurnal curves vary based on type of water use.

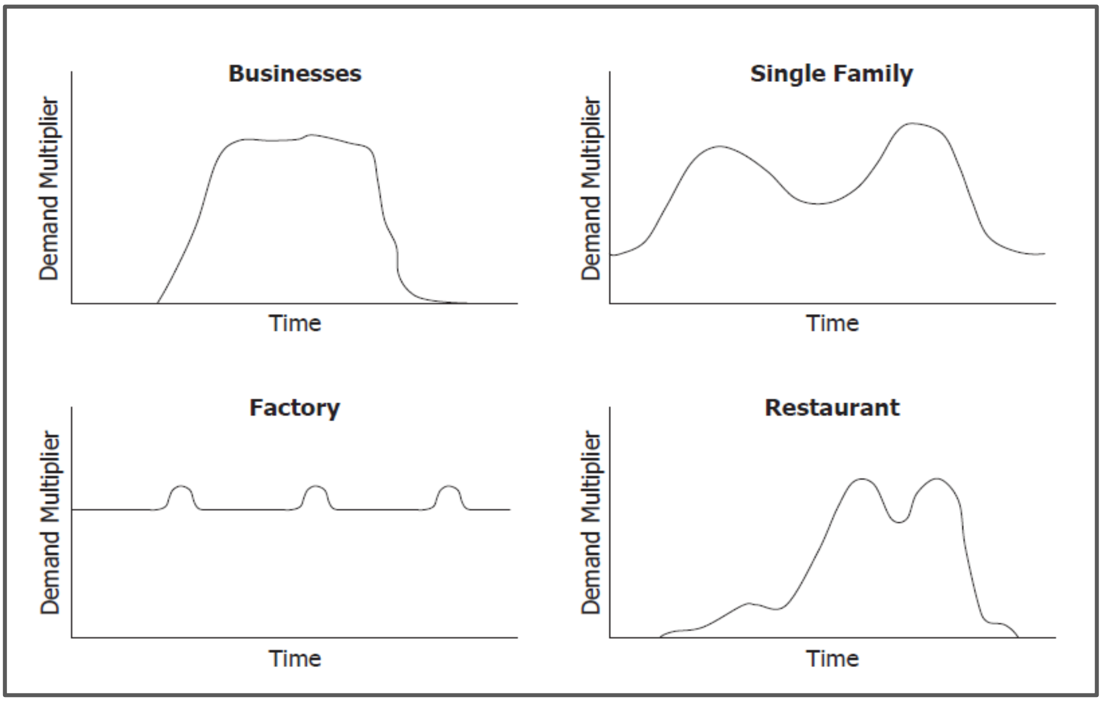



**Figure 5.3**: Typical diurnal Patterns for different types of users. Source: Walski et al. (2007)

## 5.3 Capacity assessment of the case study WDS

### 5.3.1 Introduction

The section below describes how data collected from the field work campaign was used to build the water distribution network of the case study area. Comprehensive details of model set up and simulations carried will be described.

### 5.3.2 Synopsis

The Jigawa State Water Board is the State Water Agency (SWA) responsible for the provision of water to the study area through a water distribution network consisting of PVC pipes that range between 50mm to 150 mm. This network is being fed by a 270,000 litre (270 cubic meter) tank (as can be seen in Plate 5.1) located at a base station within the residential estate. A total of 6 boreholes supply water to the tank which is then used as a source to supply piped water to the estate.

(a)

(b)

**Plate 5.1**: Source water tank for the case study area

Plate 5.1 above also shows the level of dilapidation of the tank as signs of ageing and bulging are clearly visible.

Visual inspection of the boreholes during the fieldwork campaign confirmed information provided by the Jigawa State Water Board technician, that only two of the six boreholes are operational. One reason cited as cause for this was the declining level of the ground water table which has affected output from some of the boreholes. Also, some of the pumps had broken down at the time of the field work and had not been repaired.

The age and physical condition of the tank has resulted in weaknesses; it is therefore no longer filled to its maximum capacity. Limited borehole capacity, coupled with an erratic electricity supply and lack of diesel for the backup generators are reported as reasons for infrequent filling of the tank. The tank is never completely filled due to the dilapidated condition. Once full, water is released from the tank till it empties before it is refilled again from the boreholes. According to the water supply technician from the Jigawa State Water Board, approximately 16 hours of supply is being provided to the study area daily in two supply cycles. Each supply cycle usually lasts between 7 to 8 hours before the tank needs to be refilled. However, he mentioned that the second supply cycle is not always guaranteed and is heavily dependent on electricity supply or diesel to power the generators.

### 5.3.3 System outflow

Hydraulic grade information on tank outflow rate was measured from the fieldwork campaign. The hydraulic grade information was essential as it was used to estimate the demand in the system and the hourly consumption volumes through the eight-hour supply duration. The same data was also used to estimate the flow rates of the tank and the hourly demand variation using the mass balance technique.

To collect the information mentioned above however, the researcher had to have tank level gauges installed so that variation of water level in the tank over time could be measured with some level of accuracy. Plate 5.2 shows the gauge after being installed on the tank.

**Plate 5.2**: Tank gauge after installation

Tank level was measured at the start of supply and the variation in water level was measured every hour for five days. It should be noted that filling the tank to reach the desired level before readings started was challenging as it involved switching off the boreholes at exactly the desired level. Taking this into consideration, some values were rounded off to ease calculations. This should also be noted in the subsequent results in the description of findings.

Figure 5.4 shows a box plot of the hourly change in water level in the tank for the five days. Each box represents the average change in water level at the particular hour for the five days.

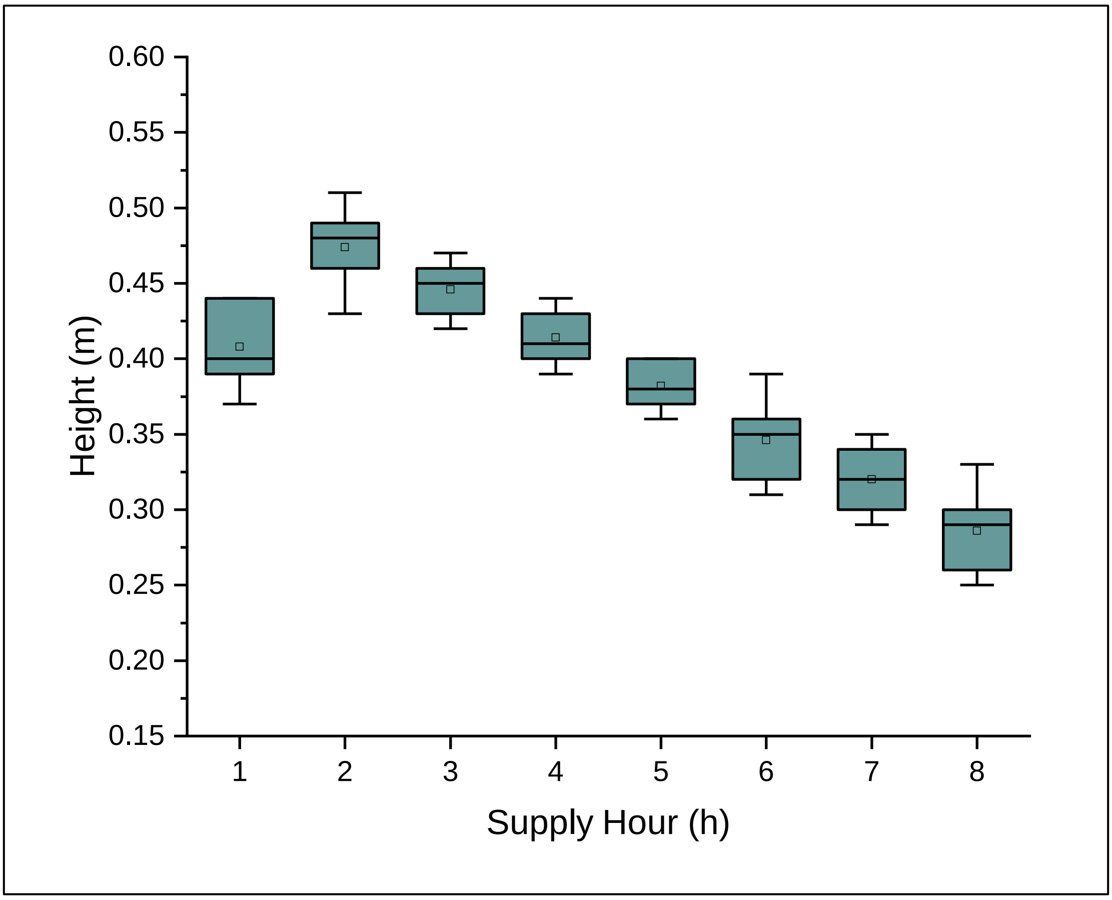



**Figure 5.4**: Average hourly change in water level over five days

The volume of water consumed every hour was obtained by multiplying average change of water level by the area of the tank.

Table 5.1 below describes the average change in heights observed for each hour through the supply duration, the equivalent volume corresponding to that height and the multiplying factor of each volume in relation to the average hourly volume.

**Table 5.1**: Average hourly height, average volume and demand multiplier

| Time (H) | Height (m) | Equivalent volume (L) | Demand multiplier |
|---|---|---|---|
| 1 | 0.41 | 24,626 | 1.06 |
| 2 | 0.47 | 28,229 | 1.22 |
| 3 | 0.45 | 27,028 | 1.17 |
| 4 | 0.41 | 24,626 | 1.06 |
| 5 | 0.38 | 22,824 | 0.99 |
| 6 | 0.35 | 21,022 | 0.91 |
| 7 | 0.32 | 19,220 | 0.83 |
| 8 | 0.29 | 17,418 | 0.75 |
| | **3.08** | **184,993** | |

Figure 5.5 below shows the hourly consumption of water during the eight-hour duration of supply. From the graph, it can be observed that the graph agrees with the pattern of consumption attributed to IWS where withdrawal is highest at the start of supply (Batish, 2003, Ingeduld et al., 2006, Sashikumar et al., 2003)., However, as mentioned by Ilaya-Ayza et al. (2017), withdrawal is likely to be high throughout the supply duration. In this case however, the fact that the source is a tank which does not refill during supply hours may be responsible for the decline in consumption rate over time. This may be attributed to the mode of operation of the network through as it is running under gravity. Consumption may also decline with time as the pressure head within the system also reduces by the emptying of the tank.

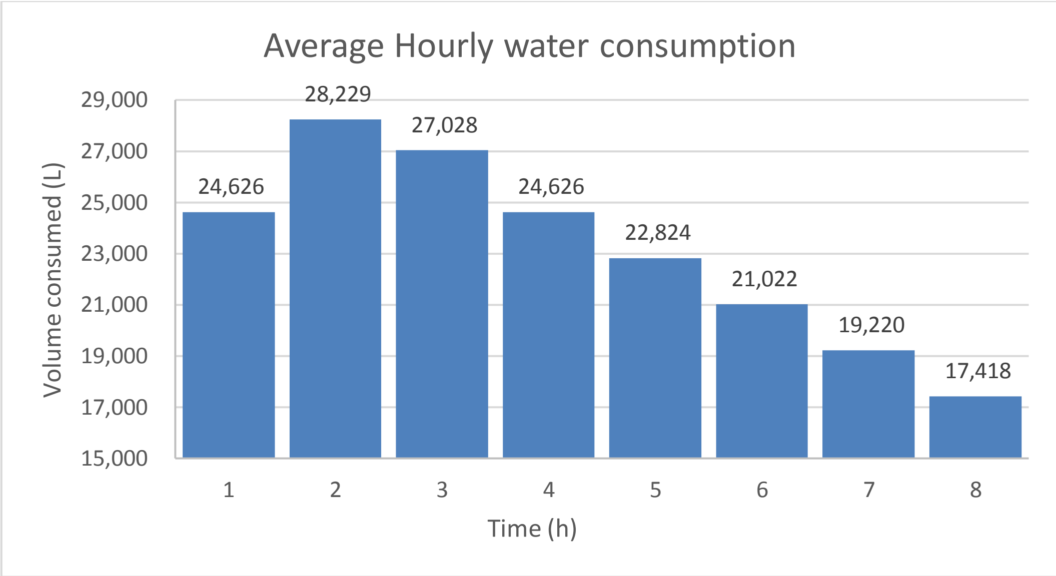



**Figure 5.5**: Average hourly consumption

The graph shows that the hourly consumption is highest at the second hour of supply where 28,229 litres of water was being consumed. The demand was least at the eighth hour where an average of 17,418 litres was being consumed. The difference between the highest and lowest consumption was 10,811 litres which represents 38% and 62% of the highest and lowest consumptions respectively.

The tank outflow rate was also calculated and Figure 5.6 shows the graph describing the tank depletion through the supply duration. It should be noted that the tank becomes empty when the water level reaches the point where the outlet is located.

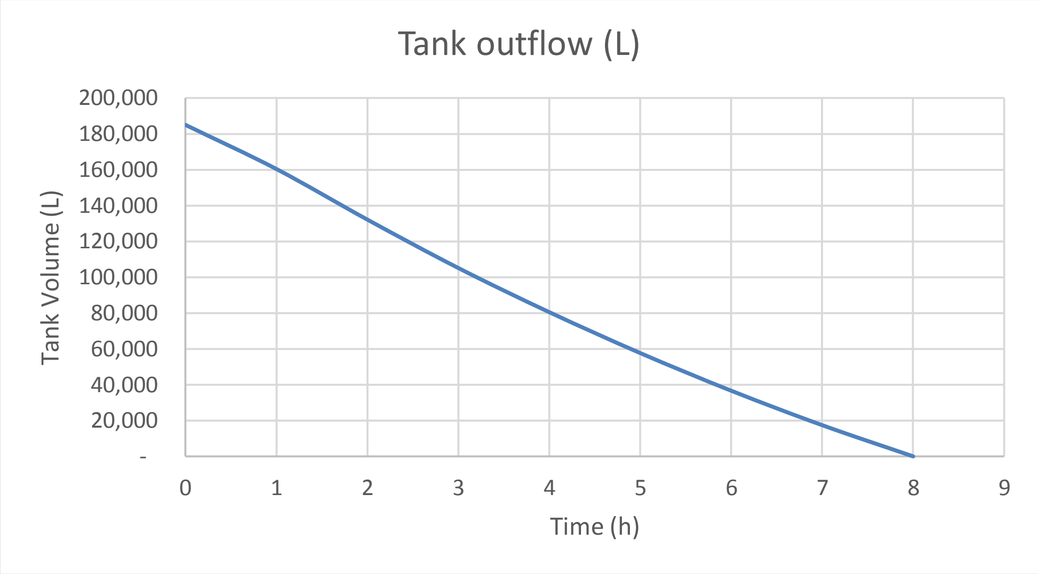



**Figure 5.6**: Average tank volume over 8 hours, averaged from data over five days

The information presented in the section above is vital for the development of a novel diurnal pattern which will be used especially in running extended period simulations.

For modelling and simulation purpose, the following additional calculations were made to provide the necessary input data for analysis:

- Tank volume is 270,000 litres but because the poor condition of the tank only about 3/4 is filled.
- Considering the outlet of the tank is 0.2m above the tank base, total available water at 3/4 tank volume is approximately 184,700 litres.
- Once valves are opened, it takes an average of 7 to 8 hours before the tank runs empty. Assuming 8 hours, average outflow per hour will be

184,700 litres/8h = 23,087.5 l/h

The total outflow from the tank was therefore equivalent to 6.41 litres/sec. This can now be equally divided within the demand nodes of the model and each node will be assigned a demand of approximately 0.23 litres/second. This information would be used in chapter six as an input parameter for modelling and simulation of the WDN of the case study area.

## 5.4 Developing the Hydraulic Model of the Case

### 5.4.1 Introduction

A computer hydraulic model of the distribution system was created using the data for the tank, pipe length and diameter, nodal elevations and the average water consumption of the study area. This information was obtained from field measurements as well as from literature. In some cases, certain assumptions were used to generate data that was otherwise unavailable. The software selected for the simulations was EPANET 2, which is a free open source software developed by the United States Environmental Protection Agency (USEPA).

The following section briefly describes EPANET as a modelling software and its basic components. It also describes how the necessary data required for simulation in EPANET was developed and entered into the software.

### 5.4.2 EPANET 2

EPANET is a hydraulic water distribution system modelling package developed by the U.S. Environmental Protection Agency's Water Supply and Water Resources Division. It performs both steady-state and extended period simulation (EPS) within pressurised pipes of a water distribution network (Rossman, 2000). EPANET operates by tracking the flow of water through each pipe and calculates the pressure at each node as well as the height of water in each tank.

By default, EPANET runs under Demand-driven assumptions in which fixed values of nodal demands are assigned and the software attempts to find nodal pressures and pipe flows that will satisfy these demands (Rossman, 2000).. However, as mentioned in chapter two of this thesis, attempts have been made to make EPANET run pressure driven analysis by modifying the source code of the software.

EPANET computes friction head loss using any of Hazen-Williams, the Darcy Weisbach or the Chezy-Manning head loss formula, including minor head losses for bends and fittings. It also has the capability of modelling both constant and variable speed pumps as well as model various other types of valves and storage tanks. In addition, EPANET can also model networks with nodes having different demand categories where each category can have a different demand pattern and can be assigned to any node in the system (Rossman, 2000).

### 5.4.3 Assumptions considered

When developing a hydraulic model for a water supply system, it is very important to make sure sufficient data has been used to represent the model as closely as possible. However, in situations were certain information is not available, reasonable assumptions can be made to complement the missing data. The following assumption in the development the case study model and the subsequent simulations carried out:

- Because the distribution network is not very old, a Hazen-Williams friction factor of 140 (PVC pipe) is assumed for all pipes. This example has been suggested for use by Arnalich (2011).

- Pipe filling and emptying is not considered in the simulations. This is because as at time of writing this thesis, EPANET does not have provisions for modelling such conditions.
- Simulations were carried out for one supply cycle.
- Nodes in the model are assumed to be representative of a cluster of households whose combined demand is represented by the demand assigned to a node.

### 5.4.4 Loading the image map

To draw the distribution network of the study area on EPANET, a map of the area is required (Rossman, 2000). This was used to trace the geometry of the distribution system identifying all the network elements as obtained from the fieldwork campaign.

Google Earth was used to capture the image of the case study area. The image was snipped and saved as a .bmp file. Two identifiable points were pinned and their coordinates were taken (i.e. Top left and bottom right). The cropped image was then loaded into EPANET.

Calculations for the dimensions of the loaded image was done using the coordinates of the earlier identified points as follows

| | | |
|---|---|---|
| Top left | 536376 | 1290127 |
| Bottom right | 537736 | 1289198 |
| | **1360** | **929** |

In the dimension dialogue box, 0, 0 was used for lower left and 1360, 929 was entered for the top right. The unit of “meters” was also selected for the maps.

Auto length options was turned on before the drawing the network. This was to ensure that values of pipe lengths drawn corresponds with actual pipe lengths on ground.

### 5.4.5 Junctions/Nodes

Nodes or junctions were first identified using the backdrop image. A node was placed on each junction where two or more pipes connect to each other. The model was simplified, such that demand from network spurs was aggregated to the nearest upstream junction. Thus, a demand node was placed at each junction, and the total demand at that point was assumed as the sum of demand from all the households along the immediate downstream spur.

The standard input parameters for a node required by EPANET to run simulations are nodal elevation and base demand. Elevations were therefore taken from Google maps. This technique is widely used in modelling (see for example (Arnalich, 2011, Dave et al., 2015). While it may introduce some inaccuracies, these are considered minimal considering the limited information available regarding the depth of excavation of the pipes and other local details.

Table 5.2 shows the values for the nodal elevations and the respective calculated demands that were used in the model. One supply run in this thesis is defined as the supply period from the time supply is switched on to the time it was switched off. This is because the main objective in this section is to identify the network performance during supply hours.

**Table 5.2**: Nodal elevations and base demand for case study model

| Node ID | Elevation (m) | Base Demand (LPS) |
|---|---|---|
| **J2** | 430 | 0 |
| **J3** | 430 | 0.23 |
| **J4** | 432 | 0.23 |
| **J5** | 431 | 0.23 |
| **J6** | 430 | 0.23 |
| **J7** | 431 | 0.23 |
| **J8** | 429 | 0.23 |
| **J11** | 432 | 0.23 |
| **J12** | 430 | 0.23 |
| **J13** | 431 | 0.23 |
| **J14** | 432 | 0.23 |
| **J15** | 431 | 0.23 |
| **J16** | 430 | 0.23 |
| **J17** | 431 | 0.23 |
| **J18** | 433 | 0.23 |
| **J19** | 433 | 0 |
| **J22** | 431 | 0.23 |
| **J23** | 429 | 0.23 |
| **J26** | 430 | 0.23 |
| **J27** | 428 | 0.23 |
| **J28** | 430 | 0.23 |
| **J29** | 427 | 0.23 |
| **J31** | 428 | 0.23 |
| **J30** | 431 | 0.23 |
| **J9** | 432 | 0.23 |
| **J10** | 432 | 0.23 |
| **J20** | 429 | 0.23 |
| **J21** | 432 | 0.23 |
| **J25** | 430 | 0.23 |
| **J24** | 428 | 0.23 |

From calculation of total outflow for in one supply run, it was estimated that each node will have a base demand of approximately 0.23 litres/second. This was then assigned evenly across all the nodes.

There was no demand assigned to node J2 as it is next to the source tank. It is recommended that nodes very close to the source are not assigned any demands (Walski et al., 2001). Node J19 was also found to be too close to node J18 (Figure 5.7) as such, no demand was assigned to the node.


**Figure 5.7**: Image of case study with the network overlaid

### 5.4.6 Pipes

Pipes were drawn to connect each of the nodes in order to correspond with the design layout of the network. Table 5.3 shows the various pipes and their corresponding lengths, diameters and roughness. Most of the pipes were of two diameters; 100 mm and 150 mm. These dimensions were assigned to each pipe according to preliminary survey of the network acquired from the Jigawa state Water Board and site inspection with the technician. The lengths of the pipes were determined automatically by EPANET using the Auto Length option when drawing the pipes.

An all pipe model (AWWA, 2012) was built where all pipes in the network were drawn to enable detailed assessment of the distribution system.

**Table 5.3**: Pipe details of the developed model

| Link ID | Length (m) | Diameter (mm) | Roughness |
|---|---|---|---|
| **Pipe 1** | 50.62 | 100 | 140 |
| **Pipe 5** | 68.72 | 150 | 140 |
| **Pipe 8** | 30.07 | 150 | 140 |
| **Pipe 15** | 74.43 | 150 | 140 |
| **Pipe 17** | 269.95 | 100 | 140 |
| **Pipe 18** | 77.97 | 150 | 140 |
| **Pipe 20** | 275.24 | 100 | 140 |
| **Pipe 28** | 68.13 | 150 | 140 |
| **Pipe 29** | 278.79 | 100 | 140 |
| **Pipe 31** | 79.85 | 150 | 140 |
| **Pipe 38** | 10.64 | 150 | 140 |
| **Pipe 39** | 94.45 | 100 | 140 |
| **Pipe 41** | 92.63 | 150 | 140 |
| **Pipe 42** | 205.07 | 100 | 140 |
| **Pipe 46** | 94.6 | 150 | 140 |
| **Pipe 48** | 208.31 | 100 | 140 |

| | | | |
|---|---|---|---|
| **Pipe 61** | 95.28 | 150 | 140 |
| **Pipe 69** | 46.3 | 150 | 140 |
| **Pipe 2** | 357.26 | 150 | 140 |
| **Pipe 3** | 202.15 | 150 | 140 |
| **Pipe 6** | 198.86 | 100 | 140 |
| **Pipe 7** | 70.82 | 150 | 140 |
| **Pipe 10** | 104.71 | 100 | 140 |
| **Pipe 11** | 100.83 | 100 | 140 |
| **Pipe 12** | 100.1 | 150 | 140 |
| **Pipe 13** | 197.51 | 100 | 140 |
| **Pipe 14** | 581.44 | 150 | 140 |
| **Pipe 16** | 649.32 | 50 | 140 |
| **Pipe 19** | 593.9 | 150 | 140 |
| **Pipe 21** | 42.6 | 100 | 140 |
| **Pipe 22** | 380.32 | 100 | 140 |
| **Pipe 23** | 34.16 | 100 | 140 |
| **Pipe 24** | 382.18 | 100 | 140 |
| **Pipe 25** | 64.1 | 100 | 140 |
| **Pipe 26** | 74.87 | 100 | 140 |
| **Pipe 27** | 156.83 | 100 | 140 |

All the pipes in the network were made of PVC material and hence a roughness coefficient of 140 was selected (Mays, 1999, Walski et al., 2007). For this simulation, and all other simulations the Hazen-Williams formula for pipe head loss was chosen as this was most commonly used formula for modelling WDNs according to Arnalich (2011).

### 5.4.7 Tank

The location of the tank was identified from google earth image and represented accordingly in the model (Figure 5.7). Physical inspection of the tank was also carried out during the field work and all the required specifications needed to run the model in EPANET were collected. Other specifications were acquired from the Jigawa State Water Board.

Tank dimensions = 7.75 X 7.75 X 4.5 (Rectangular tank)

As EPANET only accepts circular tank dimensions, conversions were made to obtain the circular equivalent of the tank dimensions. Therefore, an equivalent diameter of 8.74 m was set.

#### 5.4.7.1 Tank Elevation

From Google earth, the elevation of the point where the tank is located tank was 431 m above sea level but as the tank was found to be resting on a 0.5 m high foundation, an elevation of 431.5 m was used in in the model. (Note: elevation in this case refers to the elevation at the base of the tank).

The outlet of the tank was measured to be 0.2 m above the tank base and the height of the overflow outlet was measured to be 4.3 m (i.e. approximately 0.2 m below the top of the tank).

#### 5.4.7.2 Initial water level of tank

This parameter indicates the level of water in a tank at the start of simulation. According to the Jigawa State Water Board technician of the water level at start of supply varies depending on electricity supply and availability of diesel for the generators. However, he stated that in most cases, the tank is filled to three quarters capacity. For this reason, and to account for other initial water levels at start of supply, different values of initial tank level were selected for simulation in this thesis. This will be used to assess the effects of varying initial tank level on the system. These values are summarised in the Table 5.4 below.

**Table 5.4**: Approximate tank volumes for different initial water levels

| Water level | Approximate Tank Capacity (Litres) |
|---|---|
| Full | 246,300 |
| ¾ Full | 184,700 |
| ½ Full | 123,150 |
| ¼ Full | 61,575 |

The minimum level was taken as the outlet position at 0.2 m and the maximum level was taken as the level of the overflow at 4.3 m.

### 5.4.8 Model summary

Figure 5.8 shows the digital representation of the case study distribution network with all elements in place as obtained during the field the field work campaign.

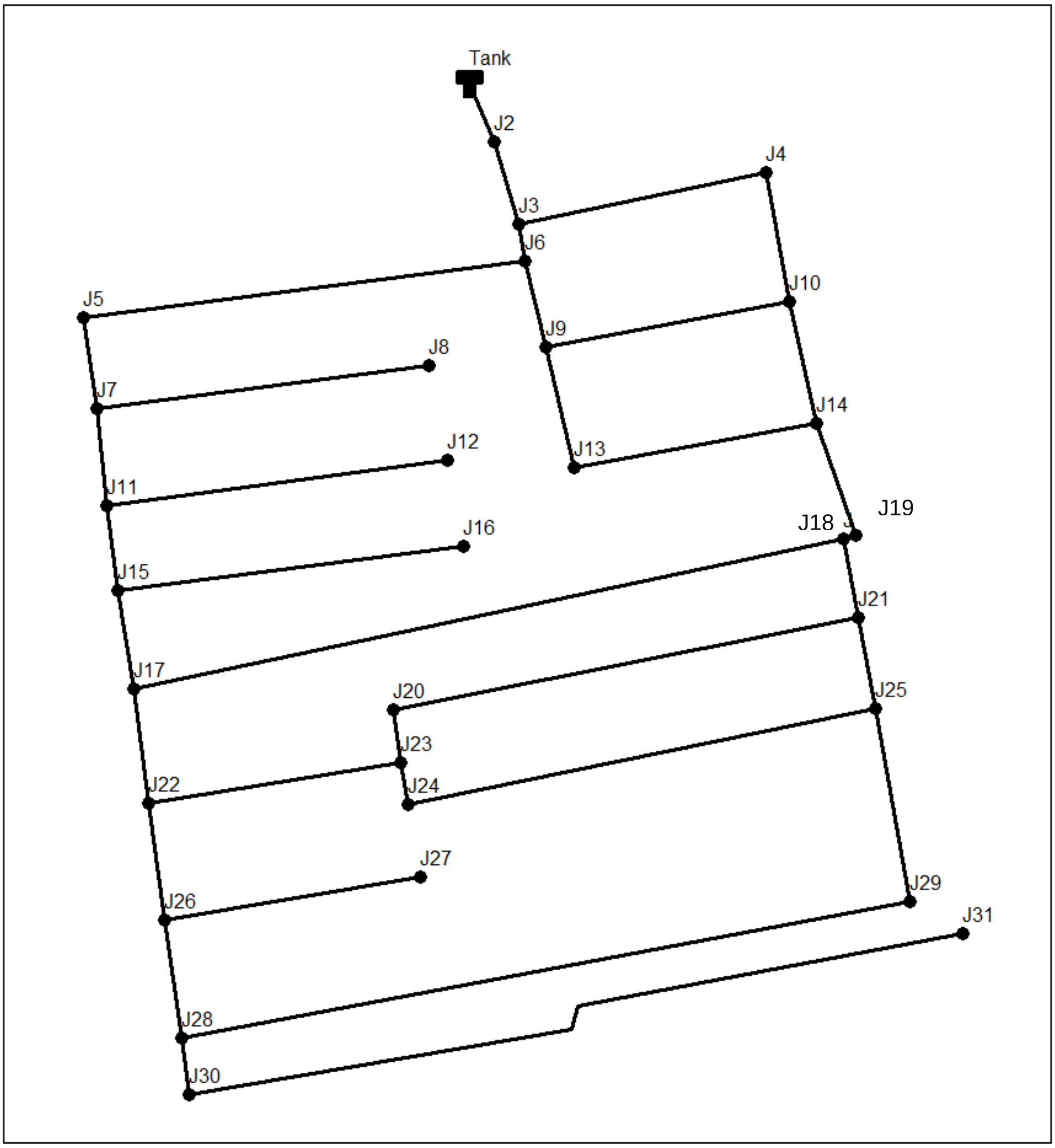



**Figure 5.8**: Water distribution network model of the case study area

In summary, the model consists of a tank, 30 nodes and 36 pipes. The total length of pipes in the model is approximately 6.41 km. Flow units selected for the hydraulic simulation was litre per second (LPS).

## 5.5 Conclusion

This chapter has introduced the basic concepts involved in modelling and simulation of water distribution networks. The major governing equations behind computer modelling software have also been discussed. Furthermore, input parameters and modelling options considered in the simulation of water distribution systems have also been discussed. The two most common analysis options are steady state analysis and extended period analysis. Each of these is important in that it can be used to assess and understand the mode of operation of a distribution system. This would be useful in this thesis as it can be used to investigate the mode of operation of the WDN of the case study in this thesis. Furthermore, operational elements required by a hydraulic modelling software were discussed.

A capacity assessment of the case study water distribution system was carried out based information collected during the field work. The findings show that should the network operate normally, the capacity of the tank would be able to satisfy the demand in the system. However, with intermittency and reports of insufficient water supply at some households and low pressure, it is concluded that there may be a number of factors that may have contributed to the poor performance of the distribution system. These factors highlighted include, poor operation of the system, over withdrawal and wastage by some households and possible leakage.

It would therefore be ideal to build a hydraulic model of the WDN to simulate its operation based on physical information of the network obtained from the fieldwork. This could provide information on how the network would perform during operation. Furthermore, it was recommended that there is a need to introduce some form of overconsumption in the network to see how it will affect the performance of the system.

The last section of this chapter described the procedure involved in the development of the hydraulic model of the case study WDN. EPANET 2 hydraulic software was chosen to be used as a tool to assess the effects of tank drain rate on the distribution network. It will also be used to estimate the effect of possible overconsumption.

# Chapter 6: Demand Driven Analysis of the Case Study WDN

## 6.1 Overview

In this chapter, section 6.2 presents EPANET analysis results of the case study WDN model developed in chapter five of this thesis. Both steady state and extended period simulation (EPS) results are presented and discussed.

The section 6.3 describes the application of potential strategies to introduce overconsumption within certain nodes in the network and assesses the implication on the whole distribution network.

Sections 6.4 and 6.5 present three models of the of the case study WDN developed based on different per capita demands. Simulation scenarios and demand patterns used to set up analysis options for these models are also presented. The section 6.6 then presents and discusses the simulation results for the three case models.

Section 6.7 concludes with the introduction of engineering interventions that can improve service delivery for the case study supply system. Simulation results from models incorporating engineering interventions into the case study network are presented.

## 6.2 Hydraulic appraisal of the developed model

### 6.2.1 Introduction

The model representation of the case study WDN is set up as described in the previous chapter to optimise its usefulness as a tool to examine the performance of the system. Both steady state and extended period simulations are presented to assess the operation of the case study WDN based on field data collected.

This is to provide an overview of how the system, despite proven to have sufficient water, is being reported to operate with intermittent supply and low pressure.

The parameters used to evaluate this are the predicted residual pressures within the system during normal and extreme conditions. Studies have shown that although quantitative data is limited, IWS has been linked to low system pressure (Kumpel and Nelson, 2016), and this is also apparent in the field study data presented in Chapter 4.

It is important to have an understanding of the guidelines for minimum required pressure set by different governments and utilities around the world. These guidelines have been set based on minimum pressure available for a number of reasons and depends on the country setting them (Kumpel and Nelson, 2016). For example in the US, a minimum pressure head of 14m is required for firefighting (Erickson et al., 2015, NFPA, 2012) while in South Africa, no less than 20m is required to prevent customers from making complaints (Jacobs and Strijdom, 2009). Similarly, Indian guidelines set minimum pressure heads of 7, 12 and 17 m to reach the top of 1, 2 and 3 storey buildings respectively (Batish, 2003). However, no set guidelines for minimum pressure requirements were found for Nigeria. The analysis carried out here will be considered with respect to the guidelines of India for analysis and discussion of results. A minimum pressure head of 7 m will be most appropriate as all the households within the case study area are 1 storey buildings. However, in systems where consumers mostly use available water for storage, lower pressure values can still be considered to have significant effect on consumption. The main effect is likely be on how long it takes to collect water.

### 6.2.2 Steady state simulation results

Initially, steady state simulations were carried out with the model to determine instantaneous residual pressures at the nodes within the distribution network. Figure 6.1 below shows the pressure distribution across the network with initial tank levels at Full and 3/4 Full. The reason for the two levels was to compare the pressure should the supply start at full tank rather than 3/4 full as the network is currently operated.

The results show that there is a significant variation of nodal pressure across the distribution network with low pressure values at various nodes. This was however expected as it is a common problem experienced by IWS systems (Lee and Schwab, 2005, Tokajian and Hashwa, 2003, Vacs Renwick, 2013). Moreover, results from the fieldwork campaign has shown that customers have complained of significantly low pressures at their taps during supply hours.

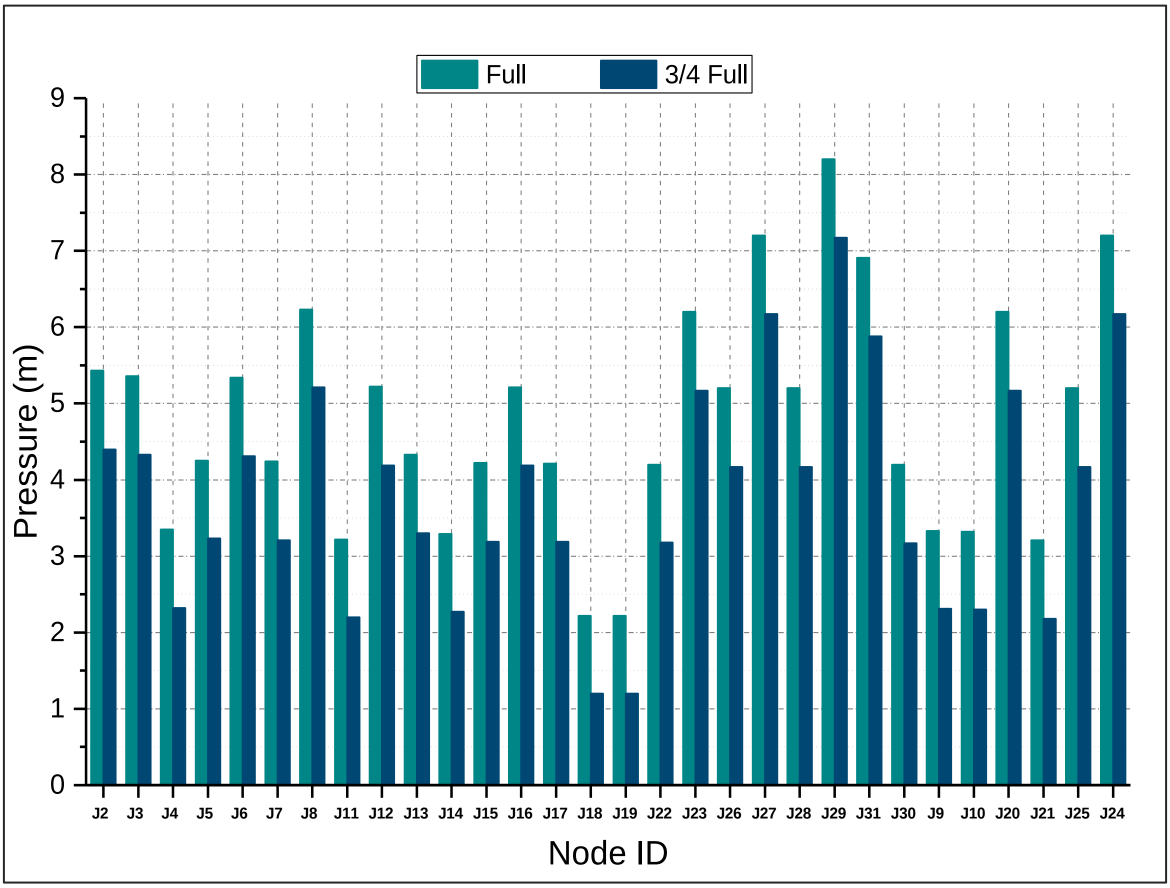



**Figure 6.1**: Nodal pressure results at varying initial tank levels

For initial tank level at 3/4 full, pressure values were ranged between a maximum of 7.17 m at node J29 and a minimum of 1.20 m at nodes J18 and J19. The average pressure across all nodes was 3.78 m. The elevations of the nodes influence the residual pressure at a node. The elevation of node J29, which is the lowest at 427 m, is the reason why it has the highest residual pressure. Nodes J18 and J19 however, have the highest elevations and this has resulted in lower residual pressure.

As expected, simulations run with the initial tank level at full gave a higher average residual pressure of 4.8 m with a maximum of 8.4 m at node J29 and a minimum of 2.22 m at nodes J18 and J19. It should be noted that 4.8 m is still less than the required 7 m minimum indicating that average pressure in the system is insufficient.

The variation of pressure within the nodes for both simulation runs were categorized into four pressure groups of ranges <2 m, 2 m to 5 m, 5 m to 7 m and >7 m as can be seen in Table 6.1. This categorization will be helpful in identifying disadvantaged nodes that will need attention in the case of network upgrade.

**Table 6.1**: Proportion of nodes by pressure category

| | **Full Tank** | | **3/4 Tank** | |
|---|---|---|---|---|
| ***Pressure (m)*** | ***Number of nodes*** | ***Percentage (%)*** | ***Number of nodes*** | ***Percentage*** |
| **>7** | 3 | 10 | 1 | 3.3 |
| **5 – 7** | 12 | 40 | 6 | 20 |
| **2 – 5** | 15 | 50 | 21 | 70 |
| **<2** | 0 | 0 | 2 | 6.6 |

Results from the simulations show that with initial tank level at 3/4 full, majority (70%) of the nodes fall within the pressure range of 2 m to 5 m. Nodes J8, J23, J27, J31, J20 and J24 (representing 20% of total nodes) have pressures falling between 5 m and 7 m. Also, node J18 and J19 (6.6% total) had pressure of less than 2 m while only node J29 had a pressure above 7 m.

However, simulation results when initial tank level is at “full” show a possibility of having significant increase in the number of nodes falling within higher pressure ranges. For example, there was a 20 percentage point increase in nodes falling within the 5 – 7 m range – an increase of 6 nodes as compared to 3/4 full. This means that there are potentially more people being served by nodes with higher pressures if the tank is filled to capacity as compared to the status quo of 3/4 full. Moreover, two more nodes had pressures above 7 m making an increase of approximately 7 percentage points when compared to simulations results at 3/4 full.

Unsurprisingly, the high pressure values obtained from the simulations (for example at nodes J24, J27, J29) corresponds with fieldwork reports of high pressure and longer supply durations from households that were closer to these nodes. Similarly, households closer to nodes J18 and J19 (i.e. nodes with highest elevation and lowest pressure) reported lower pressure and shorter duration of supply.

These low pressures observed in the system is an indicator that head within the distribution system is inadequate and that necessary measures need to be taken in order to provide better levels of service. The prevalence of low pressure within the system indicates that certain nodes will provide insufficient water to consumers they serve and hence, may result in inequity water supply.

The next section describes the results obtained from extended period simulations of the case study area highlighting the behaviour of the system during the supply cycle.

### 6.2.3 Extended period simulation (EPS) results

EPS for the model were carried out to assess the effects of the tank draining rate on nodal pressures.

The data acquired from the tank outflow was used to create a demand pattern for an eight-hour supply duration. A simplified eight-hour pattern of supply was constructed and this is shown as an EPANET image in Figure 6.2. It represents the hourly consumption ratio with respect to average hourly demand.

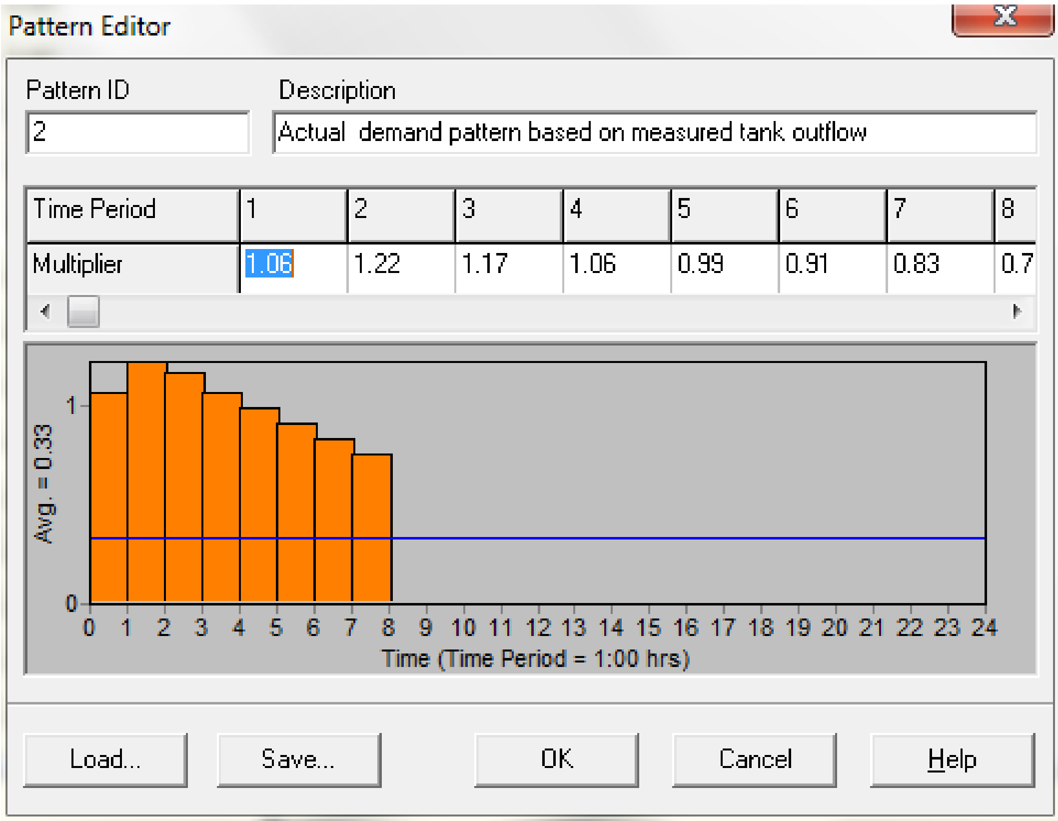



**Figure 6.2**: Demand pattern for eight-hour supply within EPANET EPS model

Creating demand patterns in EPANET involves using the pattern editor and inserting multiplying factors for each time step. However, the software has provision for inputting 24-hour time steps with 24 slots to represent a multiplier for each time step. Given that the supply duration in this study is only 8 hours, the multipliers for the demand pattern of the case study system were entered for the eight hours. The remaining slots after the eighth hour were given a multiplier value of 0, which assumes that supply has been cut off and no consumption occurs during those hours.

As described above, simulations were carried out for initial tank levels at 3/4 tank, representing the level to which the tank is filled before supply is switched on. Figure 6.3 shows the variation of tank water level through the duration of supply. It can be observed that the results agree with the collected data from field and hence, indicates some level of accuracy between the model results and the operation of the real system.

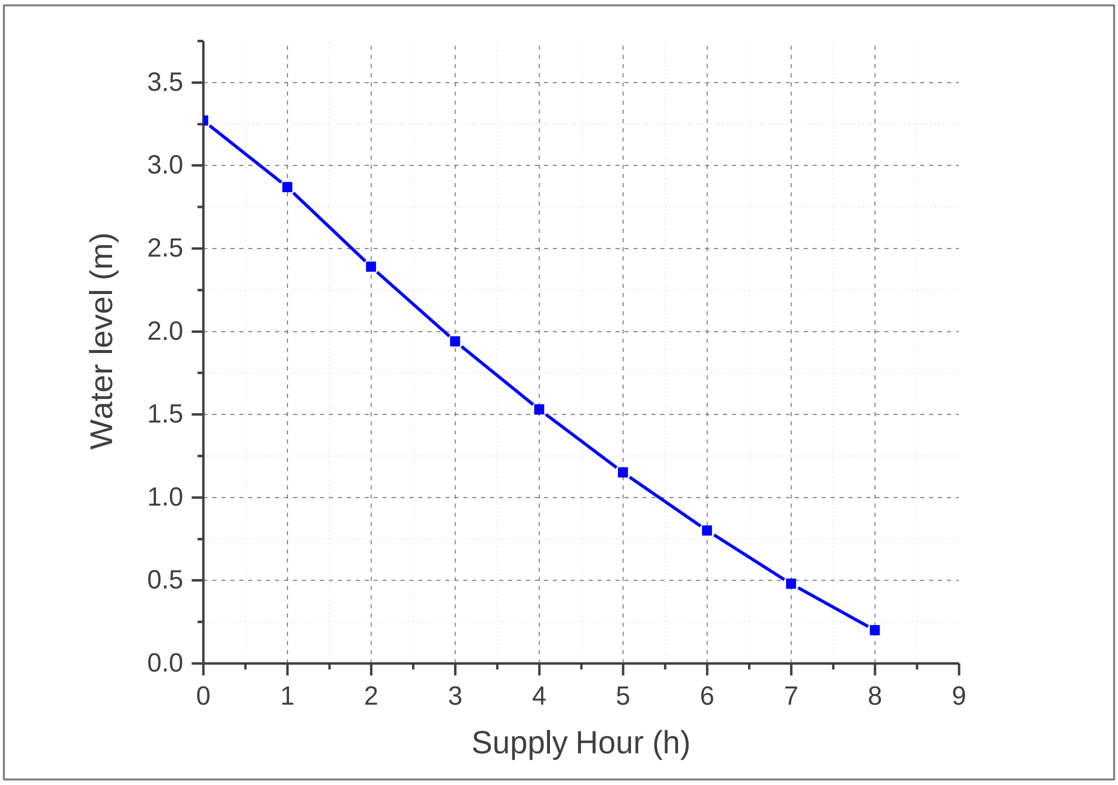



**Figure 6.3**: Simulated tank water level from EPS model with an initial tank level at 3/4 full.

The graph shows that at the eighth hour of simulation, the level of water in the tank has reduced to approximately 0.2 m. This is the minimum water level at which the tank outlet is located and hence, indicates that the tank is effectively empty.

The results from the EPS indicates a variation in pressure across the network and the presence of negative pressure in some selected nodes. In total, 7 nodes (representing 25%) of the service nodes had negative pressures before the end of supply. For example, nodes J18 and J19 were found to be the most disadvantaged nodes with an initial pressure of 1.13 m; these were the nodes with the lowest pressure during the first steady state simulations. Furthermore, these nodes could only sustain the pressure till the third hour after which the model indicated negative pressure. This means that customers at these nodes could only receive water for approximately 3 hours after supply has been switched on. This shows that in addition to have extremely low pressure less than the required 7m, these nodes will also have much lesser hours of supply compared to other advantaged nodes. Figure 6.4 shows a graph of nodes J4, J14, J18 and J21 which could not sustain sufficient pressure for the complete duration of supply.

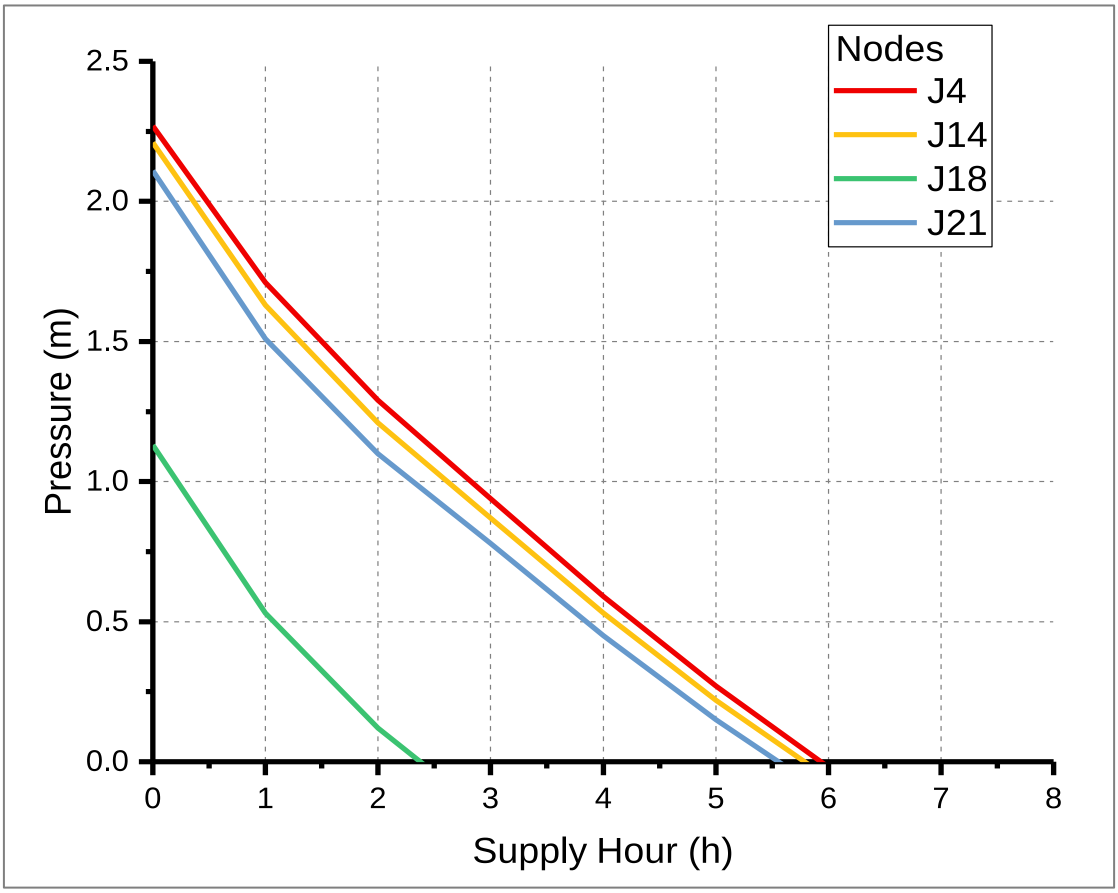



**Figure 6.4:** Variation in pressure for selected nodes with low pressure

Similarly, nodes J9, J10, J11 and J19 were also found to have low pressure at the beginning of supply. It was also observed that except for nodes J18 and J19, other nodes with lower pressure tend to receive water for about 6 hours before they run out of pressure. This may be due to the elevation of the nodes relative to the hydraulic grade line of the tank. Nevertheless, despite these nodes having slightly higher pressure than nodes J18 and J19, it is an indication of where the system is most vulnerable and where attention should be focused on when considering interventions.

Node J29 however, was observed to sustain relatively sufficient pressure through the supply period with a maximum pressure of 7.1 m and a minimum pressure of 4.1 m respectively at the beginning and end of supply. Figure 6.5 shows a graph of nodes with higher pressure throughout the supply duration. Nodes J8, J20, and J23 had pressure between 2 m and 3 m, while nodes J24, J27 and J31 had pressure above 3 m near the end of supply hours.

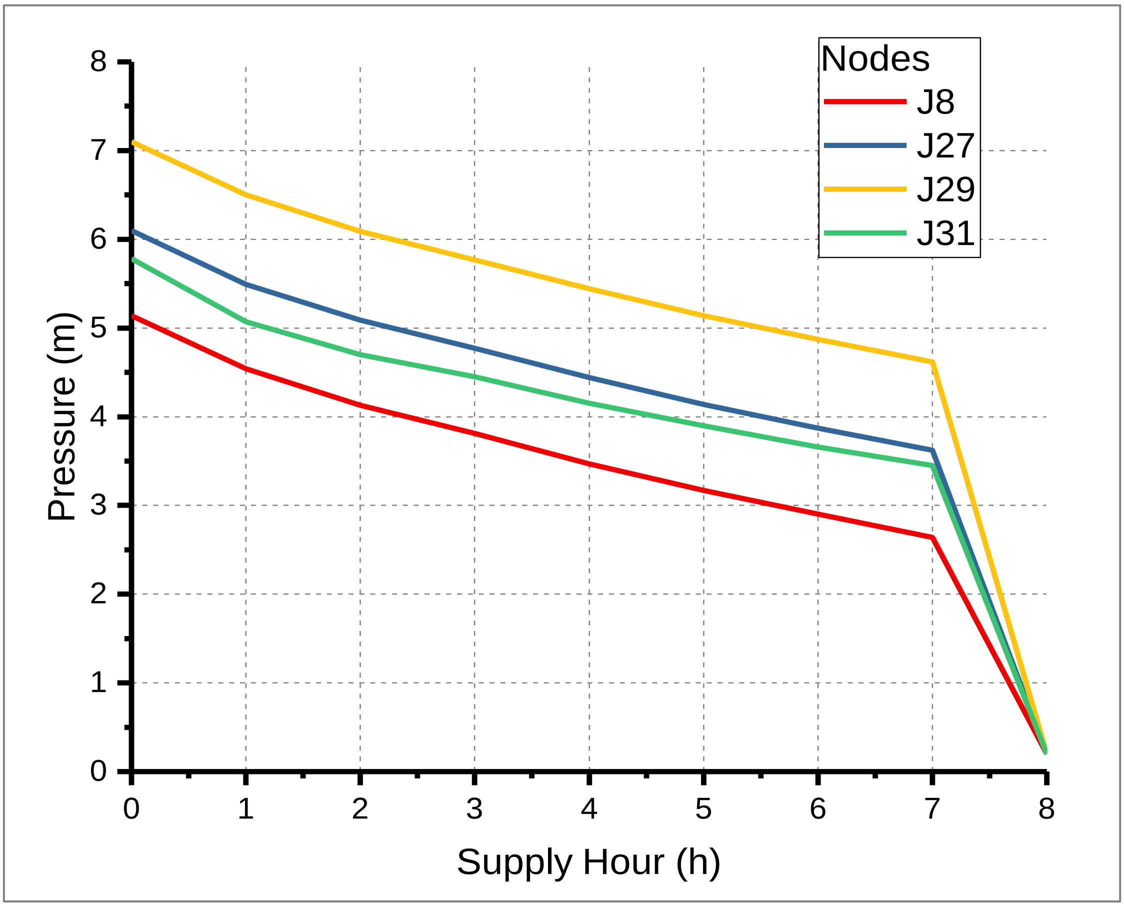



**Figure 6.5**: Variation in pressure for selected nodes with high pressure

The graph shows that nodes J27, J29 and J31 all have pressure above 3 m at the end of supply hours while node J8 had a pressure of 2.64 m at the end of the supply run. Customers receiving water from these nodes are likely to have more water than those at the disadvantaged nodes. The reason for the relatively high pressure is likely as a result of the difference in elevation between the nodes and the source tank. It should be noted that the sudden drop in the graph is as a result of the way the demand pattern has been set up. With zero representing the first hour of supply and seven representing the eighth hour of supply, the drop only shows that the next multiplier after the eighth hour is zero.

### 6.2.4 Summary

Initial simulations were carried out on the case study network and a variation of pressure has been observed across the network. The model so far only considers the idealised case under SS and EPS conditions from an initial head condition. However, it shows the likely distribution in pressure across the network assuming uniform demand. Results have shown nodes J18 and J19 to have lowest pressure values while nodes J24, J27 and J29 have the highest pressure values. This shows the viability of the model as the fieldwork results of households close to nodes J18 and J19 report lower pressure while those closer to J27 and J29 report higher pressure.

With consideration of the results from the section above, an attempt will be made to introduce modelling approaches by varying per capita demand. This may be used to further understand the behaviour of the distribution network given the limited resources.

## 6.3 Effects of overconsumption on case study WDN

### 6.3.1 Introduction

In the previous chapter, assessment of the water distribution system capacity showed that the system should be able to satisfy the demand. However, the occurrence of IWS and customer complaints suggest that the system might not be operating efficiently. The widespread use of water storage detailed in Chapter 4 suggests that there is a likelihood that overdrawing from some nodes is contributing to IWS. Furthermore, analysis of the model in the preceding section (section 6.2) highlights the variation in the distribution of pressure within nodes across the system. Reports from literature also suggests that during supply cycles in IWS systems, there tends to be higher than expected consumption at the beginning of supply, which may result in drop in pressure across the system (Kumpel and Nelson, 2016). One of the main reasons for this possible overconsumption is the use of large storage tanks by a small number of consumers who connect pumps to the distribution network. Evidence of this practice has been observed and reported during the fieldwork carried out in the case study area of this research.

It is therefore essential to carry out simulations to analyse the effects of these over withdrawals or over consumptions on the WDN model of the case study. This section therefore, aims to assess the effects of overconsumption on the already weak and underperforming WDN of the case study. The results will be compared with that of section 6.2 above to observe the effects.

One of the challenges of incorporating user behaviour into modelling is the inability to predict these behaviours. For example, a household has the freedom to choose when to switch on or off their pumps to store water in their tanks. The specification of these pumps may vary with each household such that determining each of the pump flow rate becomes a daunting task. Similarly, representing these pumps accurately within a model requires extensive data collection for households with pumps. Considering these limitations therefore, the following assumptions were made in order to simulate the effects of overconsumption on the case study WDN model:

1. Nodes with lower pressure would typically be ones requiring pumps to enable them acquire water within the first few hours of supply. This has been reported to be common in IWS systems (Batish, 2003, Ingeduld et al., 2006, Sashikumar et al., 2003).
2. These pumps are assumed to fill up the tanks in the first three hours of supply. This is because customers who receive IWS supply collect and store their entire demand within a very short time interval (Kumpel and Nelson, 2016).
3. Instead of using tank volumes, it was assumed that these lowest pressure nodes will consume, in three hours, what normal nodes would consume in the eight hours of supply.
4. Since 30% of households were reported to have pumps from the field work, 8 nodes (representing 30% of total nodes) with the lowest pressure were selected.
5. It is assumed that once these nodes consume that quantity in three hours, they have satisfied their demand and would no longer be withdrawing water from the system.

### 6.3.2 Model adjustment

With these assumptions, a demand pattern (Figurer 6.6) that would represent the three-hour consumption was created and assigned to the respective nodes. These were applied to the case study model used in the previous chapters.

From the steady state analysis results in the previous chapter, the eight nodes which had the lowest pressure were J4, J9, J10, J11, J14, J18, J21 and J30.These nodes were selected and assigned the three-hour demand pattern. Similarly, all simulations were carried out with an initial tank level at 3/4 full. This is considered to represent the normal operating conditions of the system.

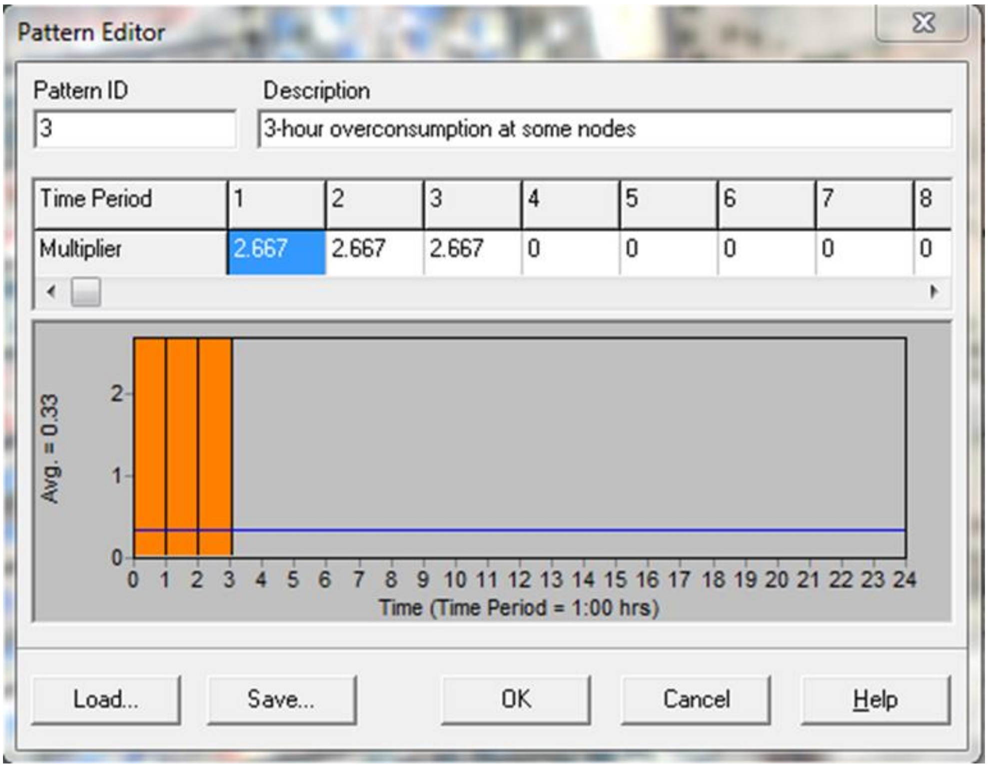



**Figure 6.6**: Three-hour demand pattern for low pressure nodes

A multiplying factor of 2.66 was assigned to each hour of simulation to represent the total demand that would have been consumed in 8 hours. This means that the baseline demand of 0.23 litres/second from the model set up in chapter 5 will still be maintained. However, for the first three hours of simulation, the concerned nodes will have more consumption rate than the other normal nodes.

### 6.3.3 Steady-state analysis results

Steady state simulation results were obtained for the model with over consumption and compared with that of section 6.2 above. For clarity, results from section 6.2 would be referred to as "normal model" while results in this section would be referred to as "overconsumption model". Figure 6.7 below shows the schematic of the network for reference purpose.


**Figure 6.7**: schematic of case study network

Results obtained for the overconsumption model have shown a decrease in pressure values within the distribution system. Figure 6.8 shows a comparison of pressure at nodes for both normal and overconsumption models.

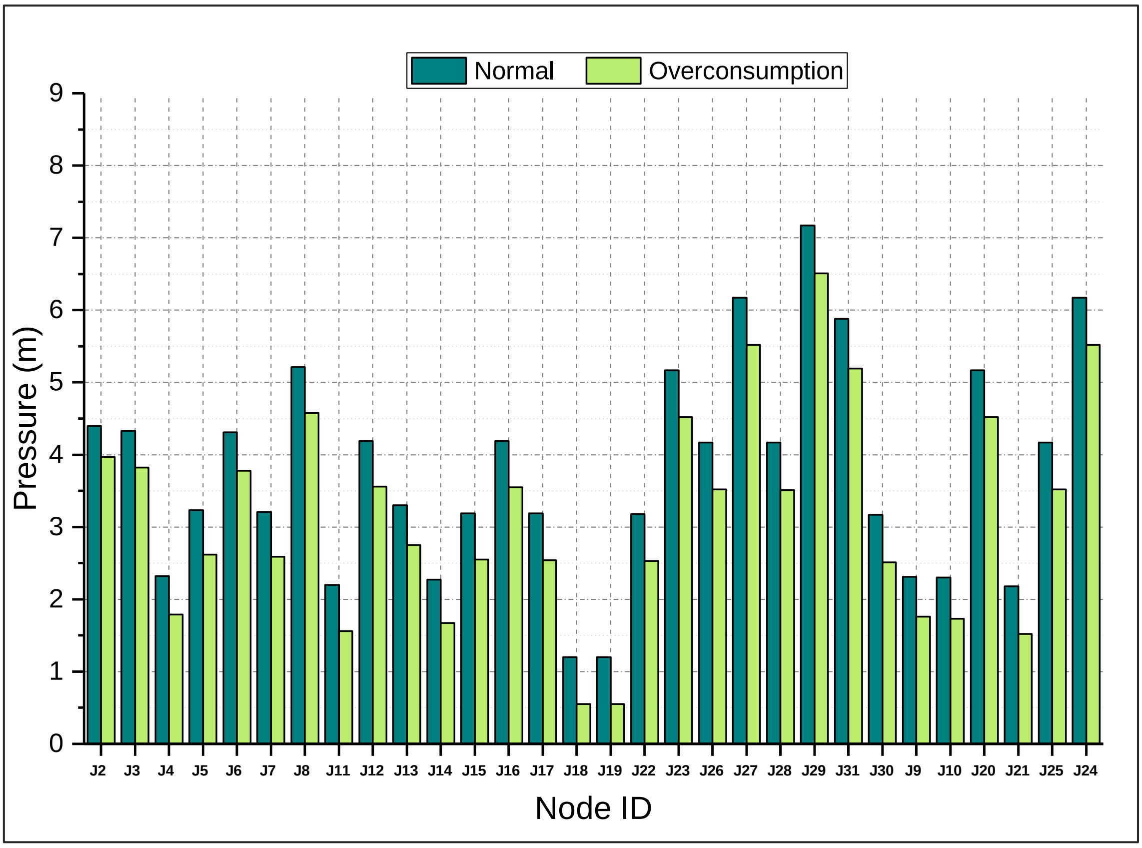



**Figure 6.8**: Steady state result comparison for normal and overconsumption model

Results show a similar trend in the variation of pressure across the network. However, with the introduction of overdraw at certain nodes, the pressure in the whole system appears to have dropped fairly uniformly. For example, pressure at node J26 decreased from 5.17 m in the normal model to 4.52 in the overconsumption model. Likewise, the pressure at node J11 also decreased from 2.2 m in the normal model to 1.56 m in the model with overdraw. It can also be observed that there is still a decrease in pressure within nodes that have been assigned to overdraw. This is because the overdraw causes a rapid decrease in tank water level.

The results of this analysis may suggest that while nodes with overdraw will receive their required demand within the first three hours of supply, there could be other nodes which might have reduced hours of supply as the tank empties.

### 6.3.4 EPS simulation results

Extended period simulations were run on the model to see the effects of overconsumption on the system. Figure 6.9 shows the graph of tank drain rate for both normal and overconsumption model.

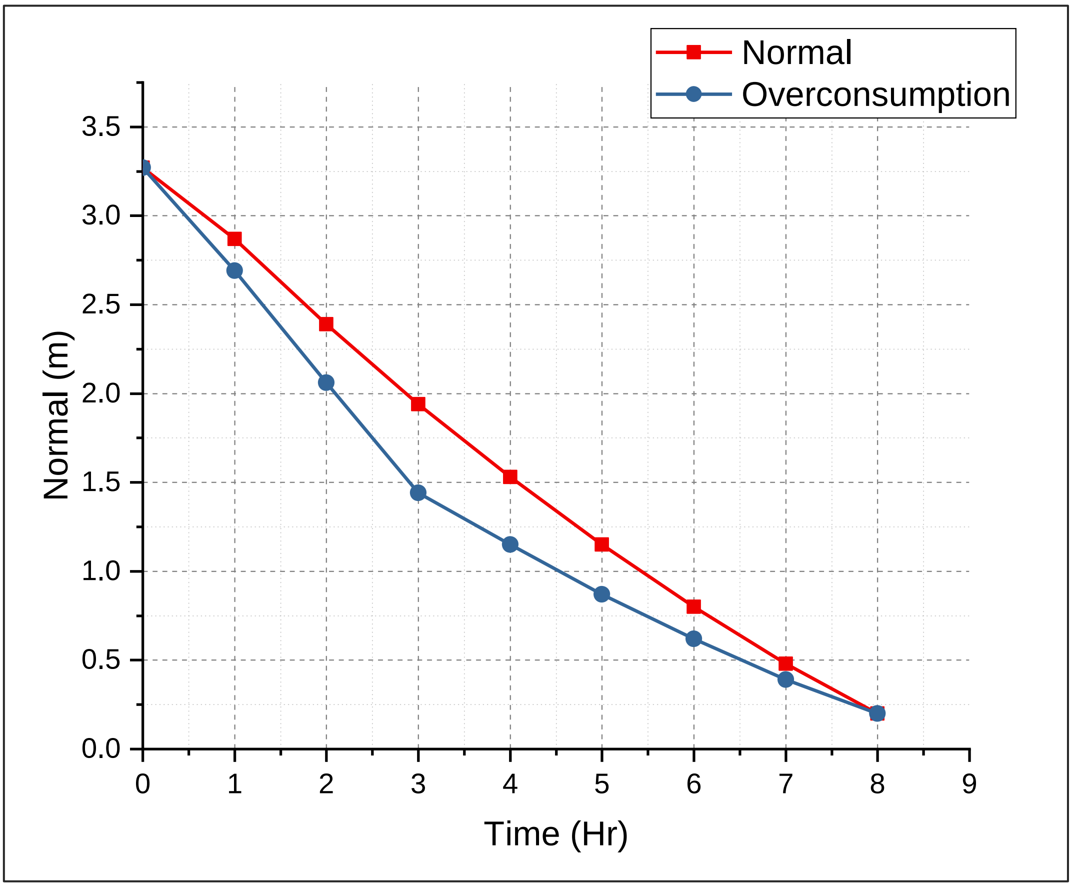



**Figure 6.9**: Tank water level for normal and overconsumption models

The graph shows that tank level was the same for both models at the beginning of supply. However, the effect of over withdrawal was immediately observed as the supply hours increased. At the third hour of supply, tank level was at 1.44 m for the over consumption model as compared to approximately 2 m for the normal model. This shows that by the time these low pressure nodes fill up their local water storage tanks, the level of the header tank would be approximately 25% lower than it would have been if there were no overconsumption. In effect, this reduction in water level will directly translate to reduction in system pressure, which may affect supply duration to multiple other nodes.

The effects of this over withdrawal were also observed at different nodes across the network. However, perhaps one point worth noting is the change in pressure over the duration of supply. For example, when the two models are compared, the maximum effect impact would be at the third hour when there is maximum withdrawal from the nodes with overconsumption. Figure 6.10 shows a graph of nodal pressures across the network at hour three of simulation.

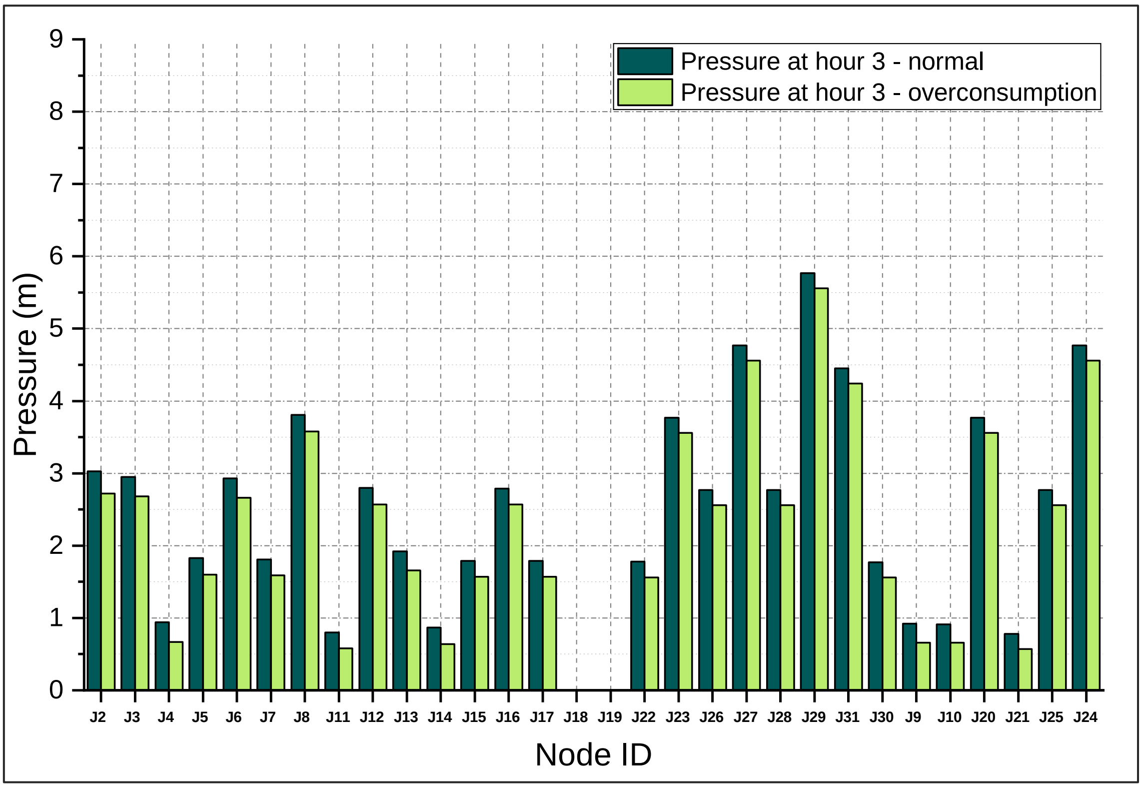



**Figure 6.10**: Nodal pressure at hour three for normal and overconsumption models

The fact that the entire system is underperforming highlights the significance of the smallest variation or reduction in pressure. What this translates to in practice is that the lesser the pressure the longer it will take a household to collect water (Klingel, 2012, Kumar, 1997, Myers, 2003), and this is likely to further drive overdraw to store sufficient water. This has been found to be the case in some countries where IWS is known to be common (Galaitsi et al., 2016), and is evident from the case study data. In this kind of setting, pressure plays a very important role in determining the coping strategies adopted by households.

### 6.3.5 Summary

The possibility of overconsumption has been tested using some assumptions. Results have shown a reduction of up to 25% in pressure across the networks as a result of certain nodes having to withdraw all their requirement in a very short duration. This may affect the supply duration at other nodes causing inequity in distribution. Therefore, there is a need to have a system where overconsumption would have less effect on the system. This can be achieved by increasing the capacity of the network or by using pumps at strategic locations in the system. Other behavioural changes may also need to be enforced. Households should not be allowed to use private pumps connected directly to the distribution mains. However, this can only be achieved if the system itself has been upgraded and households have built confidence in the mode of operation of the system.

## 6.4 Network performance with reduced demands

### 6.4.1 Introduction

Initial simulations with the case study model show significant occurrences of low pressure at several nodes across the network that is further compounded by high withdrawal rates from some households. The total demand in these first two models were both based on the field work data, assuming the header tank emptied in approximately 8 hours. However, this value was measured in a network where storage was common and hence overconsumption was very likely. This section considers the implications of higher than expected per capita demand from the households as compared to national and state standards. As discussed earlier in this thesis, demand management options have often been suggested to reduce the effects of IWS and provide continuous supply (or at least improve supply hours). Simulations are carried out here with a reduced per capita demand to assess the impact on the performance of the distribution network.

The sections below will describe the concept adopted and present the results of the simulations carried out.

### 6.4.2 Case Selection

As explained earlier in this chapter, a top-down approach was used to develop the actual model for the WDN of the case study area in EPANET. For the proposed model however, a bottom-up approach was used to develop three cases based on per capita demand. These are 46.22 lcpd (Case 1), 80 lcpd (Case 2) and 120 lcpd (Case 3). In each case base demands allocated to nodes are calculated using these per capita demands.

The first case (46.22 lcpd) is the average per capita demand of Jigawa State where the case study is located, as reported by (IBNET, 2014). The value is also similar to estimated values obtained from fieldwork, as described in chapter four of this thesis. A per capita demand of 120 lcpd was also selected as this represents the standard consumption suggested by the World Health Organisation (WHO, 2004). To close the gap between these demands, a value of 80 lcpd between the two demands was also selected to be tested. In all cases an average of 6.75 persons per household was assumed based on the fieldwork.

### 6.4.3 Proposed model demands

Nodal demands at each of the service nodes are calculated by multiplying the average household consumption by the number of households being assigned to the node.

A simple analysis was carried out to assess the tanks capacity in supplying water to the study community. This was to find out whether, under ideal operation conditions, the tank would be able to provide enough water to satisfy the demand.

The formula below was used to calculate the total demand for the study area:

$$Total\ demand\ = pphh \times dpp \times no.of\ hh, \quad (5.10)$$

where:

$pphh$ = average number of persons per household (based on fieldwork result)

$dpp$ = average demand per person

$no.of\ hh$ = number of households in the study area (505).

The values of the corresponding total demands for the three cases are shown in Table 6.2 below.

**Table 6.2**: Total daily system demand based on proposed cases

| ` | **Per capita demand *(lcpd)*** | **Total demand *(l/day)*** |
|---|---|---|
| **Case 1** | 46.22 | 158,000 |
| **Case 2** | 80 | 273,000 |
| **Case 3** | 120 | 409,000 |

Figure 6.11 illustrates the daily demands for the three cases and how they compare with the quantity of water in the tank at different initial water levels as previously illustrated in Table 5.4. The graph shows that with a full tank, the total daily demand for Case 1 will be satisfied with a surplus of approximately 88 cubic meters. Similarly, tank level at 3/4 will also satisfy the daily demand for Case 1 with an excess of 27 cubic meters. All other tank levels (1/2 full and 1/4 full) will fall short of satisfying the demand for Case 1.

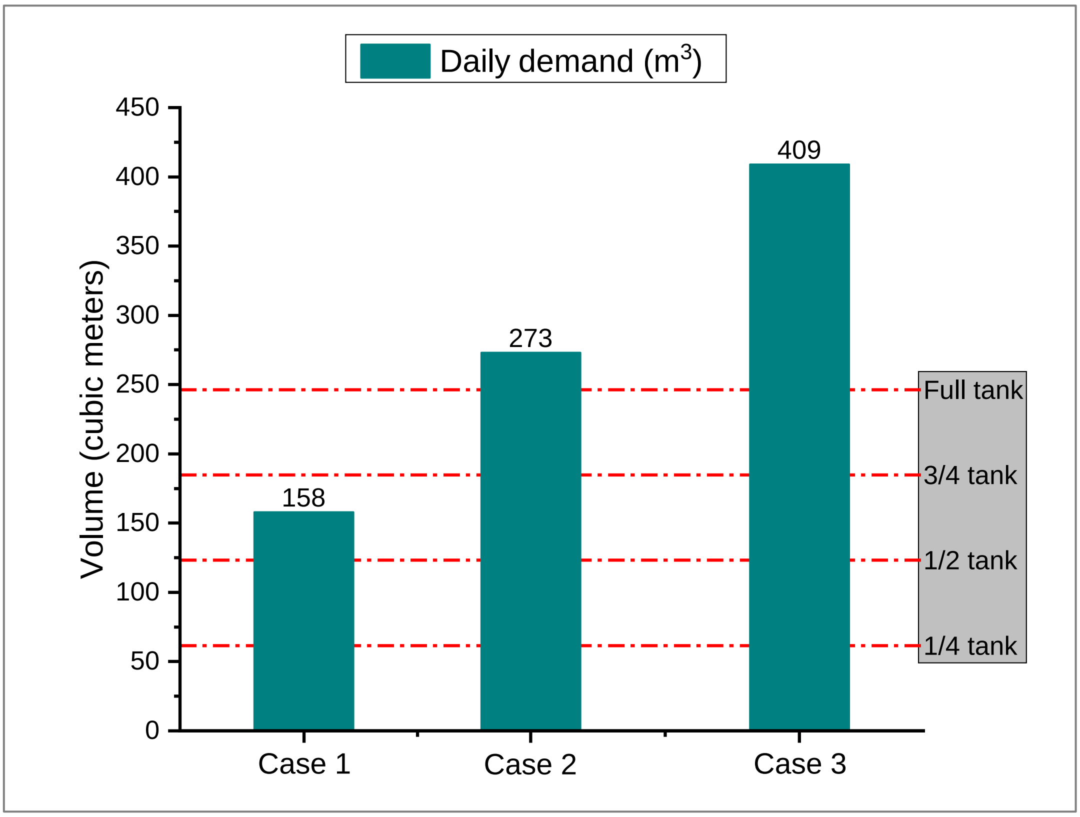



**Figure 6.11**: Comparison of case daily demand to varying tank levels

For Case 2, available water at full tank falls short of the required daily demand with a deficit of approximately 27 cubic meters. This means that it can only provide 90% of the total daily demand. Likewise, tank level at 3/4 can only satisfy 68% of the daily demand. However, with Case 3 – which is the WHO standard, the total household demand is significantly higher than the capacity of the tank. This means that given normal operating conditions the tank will only be able to supply about 60% of the demand.

It should be noted however that the statements above are for one supply cycle. If two cycles are considered, the demand of the system daily demand of the system would be met even when the tank is filled to 3/4 full. So therefore, if there should be any failure or shortfall in the demand with two steady supply cycles, the failure may be attributed to low pressures in some places and behaviours of households who consume high amounts of water.

## 6.5 Setting up the reduced demand model

### 6.5.1 Simulation Scenarios

The EPANET simulations aim to assess the performance of the reduced demand models under the three different operational regimes. It is assumed that in terms of tank refilling, only one supply cycle over a 24-hour period is considered, which is the worst-case scenario. Both steady state and EPS were run for each scenario.

All scenarios were run using four different initial tank levels in order to assess how each affect simulation results. The initial tank levels used were: Full tank, ¾ Full, ½ full and ¼ full.

### 6.5.2 Selection of demand patterns (diurnal patterns)

The three daily demands were each applied through two different demand patterns as described below.

#### 6.5.2.1 Demand Pattern 1

The first demand pattern follows average daily demand variations with peak factors in the morning and in the evening. Since the area is residential, a typical residential diurnal curve (Figure 6.12) is adopted from literature and modified for use in the simulations (Arnalich, 2011).

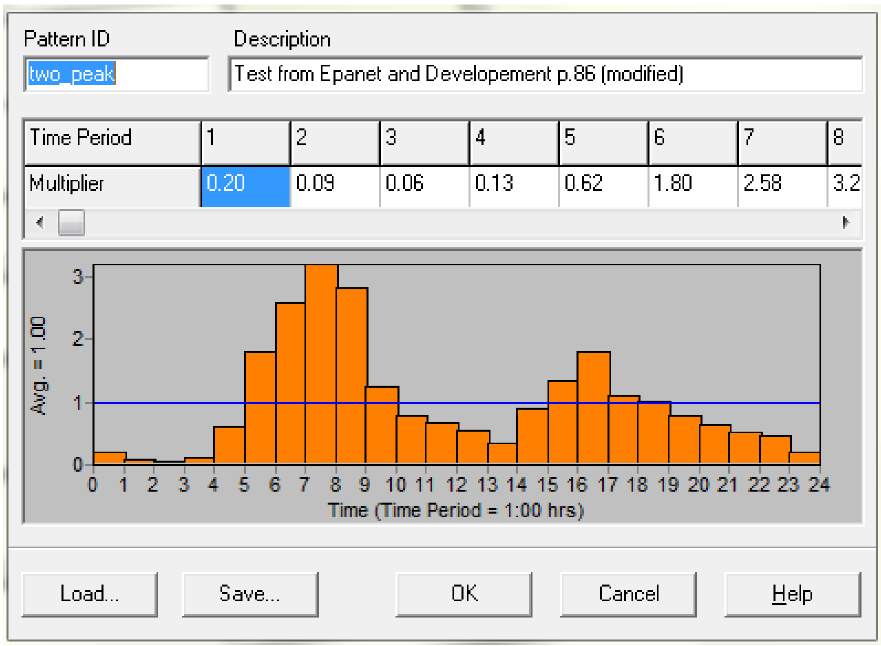



**Figure 6.12**: Demand pattern 1 with highest of the two peaks occurring in the morning hours.

In this case it is assumed that there will be two peak factors where demands are expected to be high during the day. This is usually assumed true for a 24-hour supply service and will be used to assess the performance of the case study network with the assumption that it is operating under normal conditions. In the results section, this pattern is referred to as “Two peak”.

### 6.5.2.2 Demand Pattern 2

The second demand pattern has maximum withdrawal at the beginning of supply. This assumes that water users who receive IWS services collect as much water as possible when supply is switched on, for storage to use when supply is switched off (De Marchis et al., 2010). This, as seen in Figure 6.13, results in a pattern with one peak factor, having maximum withdrawal at the beginning of supply and minimum withdrawal at the end. Another reason for adopting this demand pattern is because of its similarity with the pattern observed through tank volume measurements discussed earlier in this chapter. This presents a novel approach for simulating networks operating under intermittent conditions.

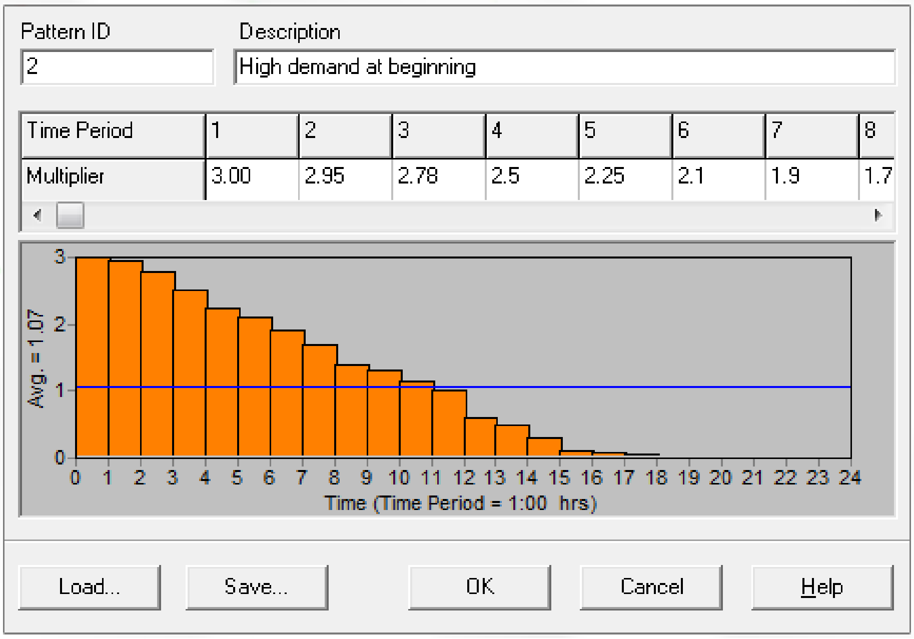



**Figure 6.13**: Demand Pattern 2 with maximum withdrawal at beginning of supply

In this case, it is assumed that demand at the first hour of supply is up to three times higher than the average daily demand and it gradually reduces over the supply periods as consumers fill up their storage containers.

This demand pattern is considered to be similar to the pattern generated from the field data, but in this case, the multiplying factors are spread over 24 hours. In other words, this demand pattern represents user behaviour during supply period.

### 6.5.2.3 Pattern Start time

When identifying and working with demand patterns, it is important to know how to reference the pattern start time. In one case, it may refer to the actual time of the day corresponding to that hour (for example, hour 3 is equivalent to 3:00 am). In other cases however, it may refer to the time at which simulation is started (this could be the time when supply is switched on) (Walski et al., 2007).

Simulation start time for demand pattern of pattern 1 assumes that the diurnal curve refers to the equivalent time of the day (i.e. hour 0 start time means midnight) while simulation start time for pattern 2 refers to time at which supply starts, which is more likely to be around 6-7am.

## 6.6 Analysis of the reduced demand models

### 6.6.1 Analysis approach

In this section, the main objective is to find the extent to which the distribution system of the case study area can operate under extreme conditions. Two analyses are carried out for steady-state simulations: the maximum hour demand conditions, and the minimum hour demand conditions (see section 5.2.5).

Review of literature revealed that multiplying factors during intermittent water supply can reach as high as 5 to 6 in some developing countries due to excessive withdrawal usually at the beginning of supply (Andey and Kelkar, 2007). However, these patterns mentioned are for large urban water distribution networks. For this reason therefore, a set of multiplying factors ranging from 1 to 5 were selected for the steady state simulation scenarios of the proposed cases.

In maximum hour demand analysis, tank elevations are set at the lowest normal level and if not known, set as half- full (AWWA, 2018). Based on the field work carried out on the case study area, it was found that there are times (although very rare) when supply is switched on with tank level below half. For this reason, and to further assess the extent at which the tank level at start of supply may affect residual pressure, half tank was selected for the maximum hour analysis.

Simulations were run for various multiplying factors ranging from MF 1.0 to MF 5.0 to observe the versatility of the distribution network. These ranges of multiplying factors were chosen in order to reflect the excessive withdrawal by consumers as a result of intermittent supply. Only results of MF1.0 to MF3.5 are discussed as results for MF 4.0 to MF 5.0 had such large values of negative pressure that they were considered to be irrelevant to the study. This is because high negative pressure values for example, values below -10 m, are not feasible and are only representative of vapour pressure (AWWA, 2018). When this happens it simply means that system has failed and cannot be related to real situations.

### 6.6.2 Reduced Demand Model Results

This section highlights the results obtained for maximum hour demand analysis of the network for the different demands and multiplying factors. Simulations were carried out at different average daily consumption of 46 lcpd, 80 lcpd and 120 lcpd each with a multiplying factor ranging from MF 1.0 to MF 5.0.

In addition to finding out the nodal pressure values, the analysis was also used to evaluate the extent at which multiplying factors cause the network to fail.

#### 6.6.2.1 Case 1 – 46 lcpd

Results from maximum hour demand analysis in Figure 6.14, show that for scenario 46 lcpd starting at half tank, the values of pressure at normal multiplying factor of (i.e. MF 1.0) is highest at node J29 with a pressure of 6.58 m while the lowest value was 0.58 m at nodes J18 and J19. The average pressure across the distribution network at MF 1.0 was 3.15 m, which is about 50% lower than the highest nodal pressure in the simulation run.

Values of pressure within the network kept reducing as the multiplying factors were increased. At a MF 3.0 with half tank as the initial tank level, pressure was highest at node J29 with a value of 6.08 m while it was lowest at nodes J18 and J19 with a value of 0.11 m. This run gave an average nodal pressure of 2.68 m across the network. At a multiplying factor of 3.5 however, the system was unable to supply enough pressure to satisfy the demand as negative pressure of -0.07 was observed at nodes J18 and J19.

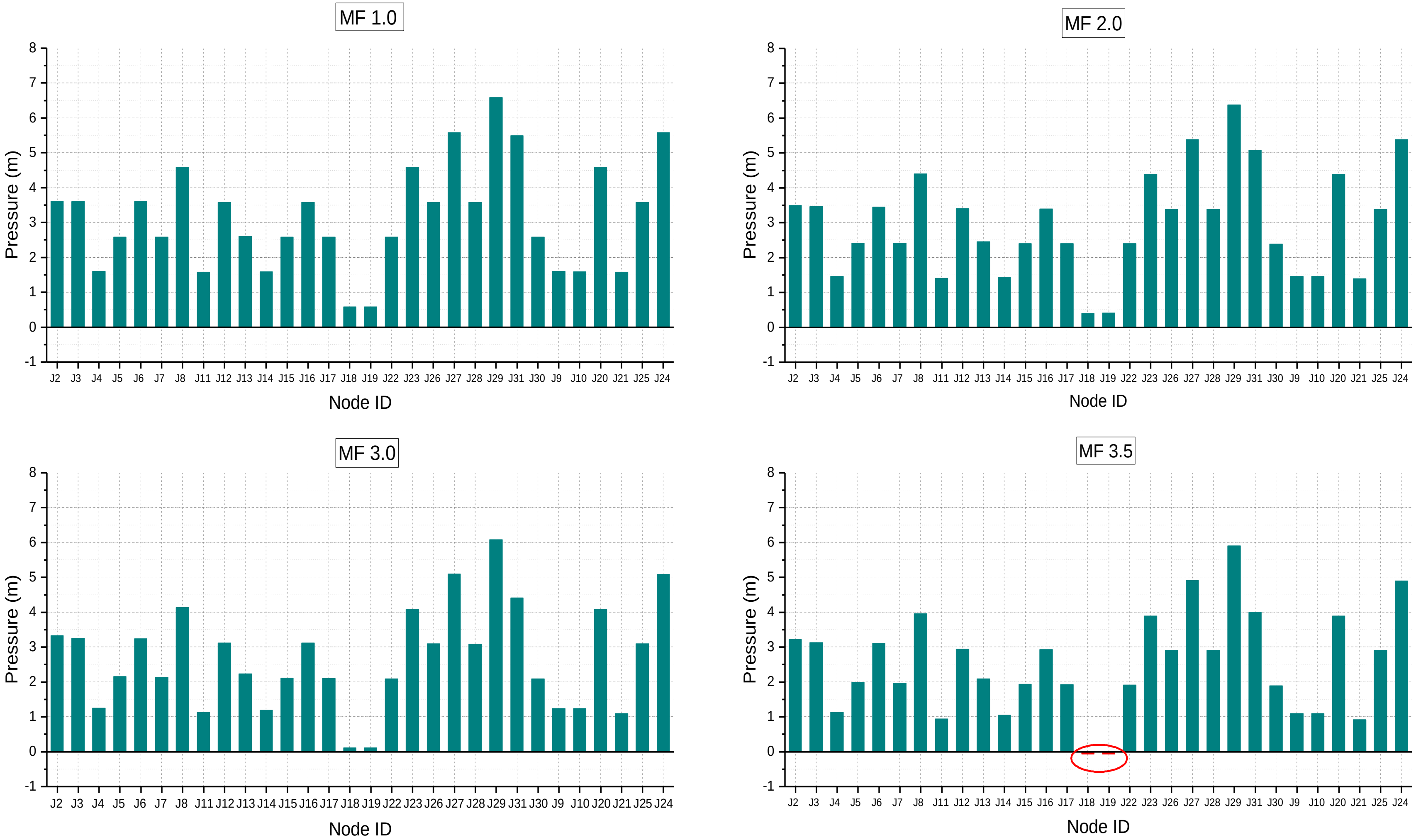



**Figure 6.14**: Pressure values for maximum hour demand analysis of 46 lcpd

#### 6.6.2.2 Case 2 – 80 lcpd

Figure 6.15 below showed that simulations for the case of 80 lcpd as base demand showed the highest nodal pressure obtained at MF 1.0 was 6.44 m at node J29 and the lowest was 0.45 m both at nodes J18 and J19. The average pressure across the network for this multiplying factor was 3.02 m. The network was not able to provide enough pressure when the multiplying factor was increased to MF 2.0 with negative values being observed at nodes J18 and J19.

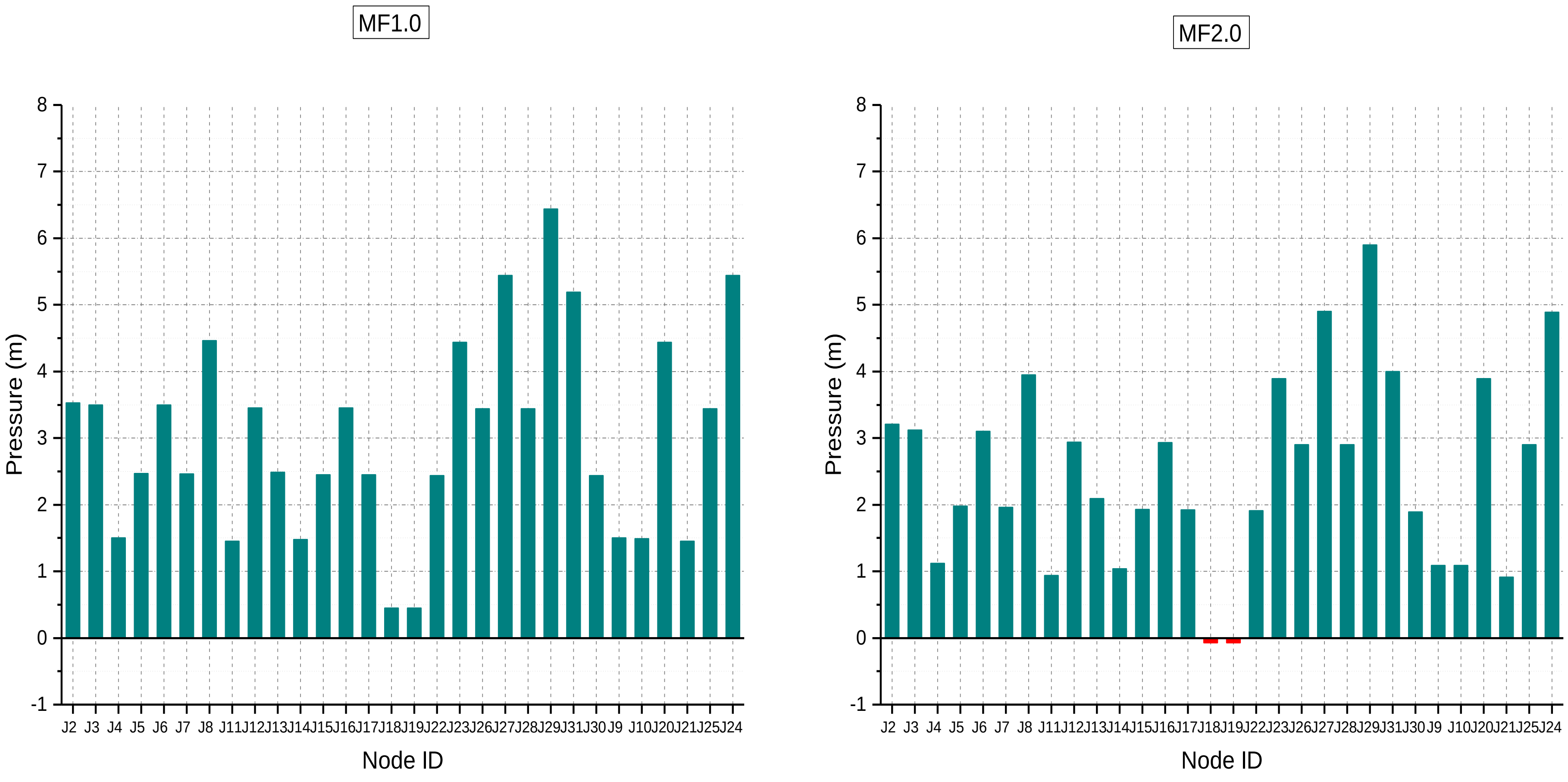



**Figure 6.15**: Pressure values for maximum hour demand analysis of 80 lcpd

#### 6.6.2.3 Case 3 – 120 lcpd

Figure 6.16 below shows results of nodal pressure obtained for maximum hour demand analysis of 120 lcpd at MF 1.0 and MF 2.0. The results show that at MF 1.0, nodal pressure at J29 was highest with a value of 6.25 m while nodes J18 and J19 had the lowest pressure of 0.26 and 0.27 respectively. This very low values will make consumers complain and possibly adopt coping strategies like use of pumps (Jacobs and Strijdom, 2009). The average pressure in this scenario across the distribution network was 2.83 m. This is well below the minimum required pressure of 7 m and will be unacceptable in many countries.

Pressure at the nodes recorded for MF 2.0 were however observed to have negative values of -0.75 m at both nodes J18 and J19. The average pressure in this run was 1.84 m with a maximum observed pressure of 5.19 m at node J29.

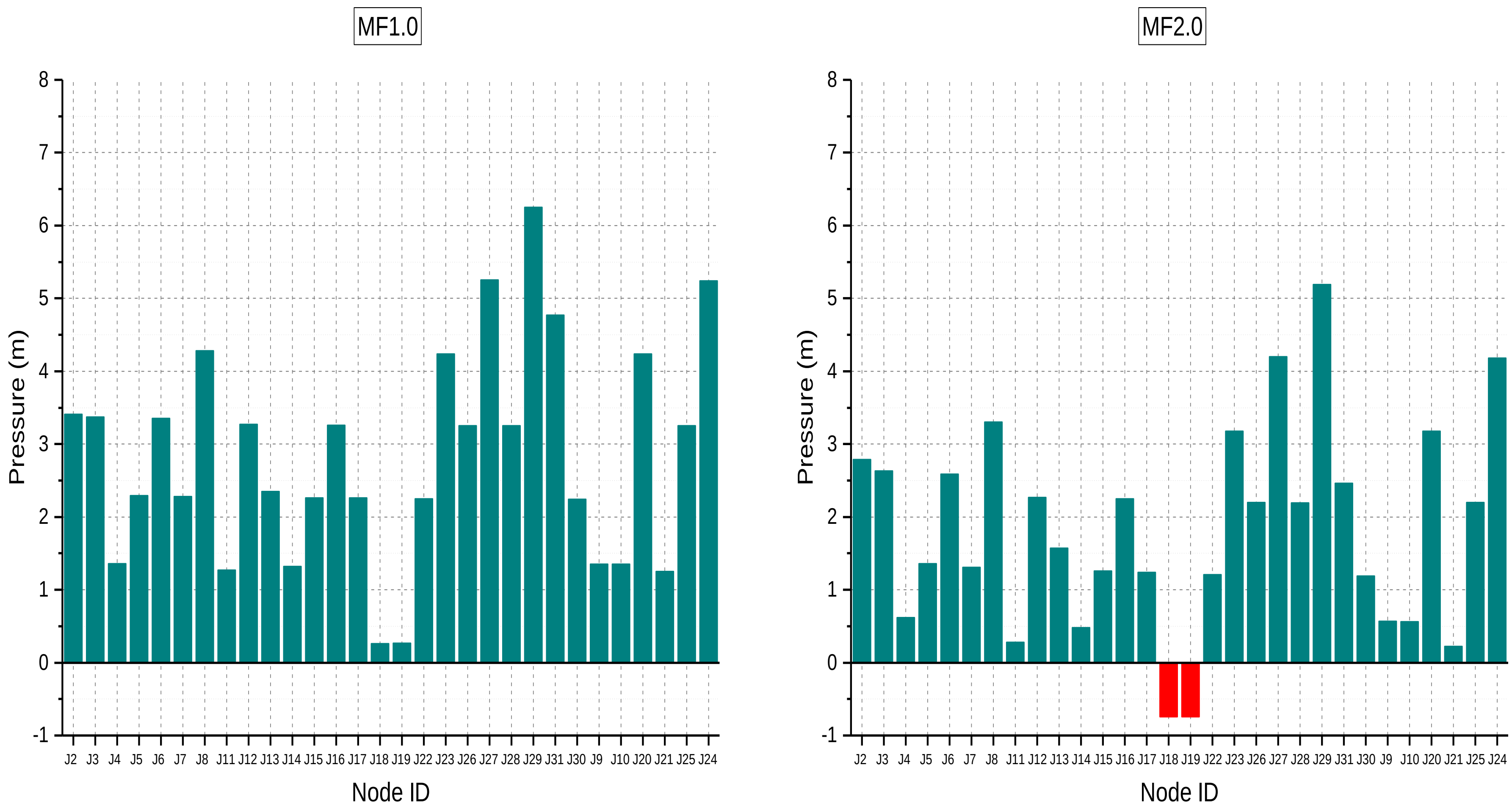



**Figure 6.16**: Pressure values for maximum hour demand analysis of 120 lcpd

Table 6.3 summarizes the results from the maximum hour demand analysis carried out for all the cases and scenarios. The results show that case 1 with 46 lcpd had more potential to provide higher pressure at more nodes than the other cases (80 lcpd and 120 lcpd). From the table it can be observed that at with a multiplying factor of 3.0, Case 1 could still provide a pressure of 6.08 m in the network. However, other disadvantaged nodes were observed to have pressure values of 0.11 m.

For Case 2 and Case 3 however, only results for MF 1.0 had all positive pressure across the network. Although there were nodes with higher pressure for the other multiplying factors, there were significant occurrence of negative pressure across the network when the multiplying factors were increased. This means that the system would not have been able to satisfy the demand should the multiplying factors be increased from 1.0.

This means that with the tank at half full level, the fundamental issue is the presence of low pressure in the network rather than over consumption.

**Table 6.3**: Summary of nodal pressure across network for different multiplying factors

| | 46 lcpd | | | 80 lcpd | | | 120 lcpd | | |
|---|---|---|---|---|---|---|---|---|---|
| | Max_P(m) | Min_P(m) | Avg_P(m) | Max_P(m) | Min_P(m) | Avg_P(m) | Max_P(m) | Min_P(m) | Avg_P(m) |
| **MF 1.0** | 6.58 | 0.58 | 3.15 | 6.44 | 0.45 | 3.02 | 6.25 | 0.26 | 2.83 |
| **MF 2.0** | 6.38 | 0.40 | 2.96 | 5.9 | N/P | - | 5.19 | N/P | - |
| **MF 2.5** | 6.25 | 0.27 | 2.83 | 5.51 | N/P | - | 4.45 | N/P | - |
| **MF 3.0** | 6.08 | 0.11 | 2.68 | 5.06 | N/P | - | 3.57 | N/P | - |
| **MF 3.5** | 5.9 | N/P | - | 5.43 | N/P | - | 2.55 | N/P | - |

Max P – Maximum residual pressure

Min P – Minimum residual pressure

Avg P – Average residual pressure

MF – Multiplying factor

N/P – Negative pressure

As mentioned earlier, the purpose of the maximum hour demand analysis is to verify the minimum possible pressure that a network can provide under the highest possible loading. This is important as systems delivering IWS are characterized by low and negative pressure (Klingel, 2012, Kumpel and Nelson, 2016). The results from the maximum hour demand analysis will help identify, among the proposed models, which nodes may need intervention and possible improvement. For example, the nodes with the lowest pressure value can be used as benchmarks for achieving a minimum standard pressure of 7m across the system.

### 6.6.3 Effect of demand pattern on Tank level

EPS were carried out using the same three daily demands and two demand patterns to assess the effect of the demand patterns on the water level of the header tank and to evaluate how the tank level varies over the simulation period.

Figures 6.17 and 6.18 show the results for 46 lcpd, 80 lcpd and 120 lcpd models respectively and are further discussed in the next sections.

#### 6.6.3.1 Demand Pattern 1 results

Figure 6.17(a) shows tank levels after an EPS simulation of Case 1 (46 lcpd) with demand pattern 1. It can be observed that the first few hours of supply have minimal decline in tank level, as the demand pattern represents nighttime hours. The simulation shows that with a full tank at the start, 24-hour supply could be achieved and approximately 1.3 m of water would be left at the end of the period. At 3/4 tank level there would still be 0.29 m of water left at the end of the period. This would not provide enough pressure to all the nodes in the network, however, certain advantaged nodes (e.g. nodes J24, J27 and J29) are likely to have more hours of supply. Simulations with initial tank levels at 1/2 and 1/4 capacity showed that water in the tank would be drained completely in 16 and 12.5 hours respectively.

For case 2 (80 lcpd), Figure 6.17(b) shows that at full tank, supply will be available for approximately 19 hours, meaning that the tank would not be able to provide 24-hour supply. Additionally, a number of nodes, especially those with high elevation, would have insufficient pressure at the end of the of supply period. Tank levels reach the minimum for 3/4, 1/2 and 1/4 tank capacities at simulation times of 15 h, 14 h and 10 h respectively. The effect of the pattern peak hours is clearly visible in the graph as they show a depression at the corresponding times. Overall, if the network is subjected to 80 lcpd demands at full tank, it is not able to provide continuous supply.

Simulation results for Case 3 (120 lcpd) under demand pattern 1 are represented in Figure 6.17(c). The graph shows that available water would last only about 15 h before the tank runs empty. Water at the tank drains completely at 14 h, 12 h and 9 h for initial tank levels of 3/4, 1/2 and 1/4 respectively.

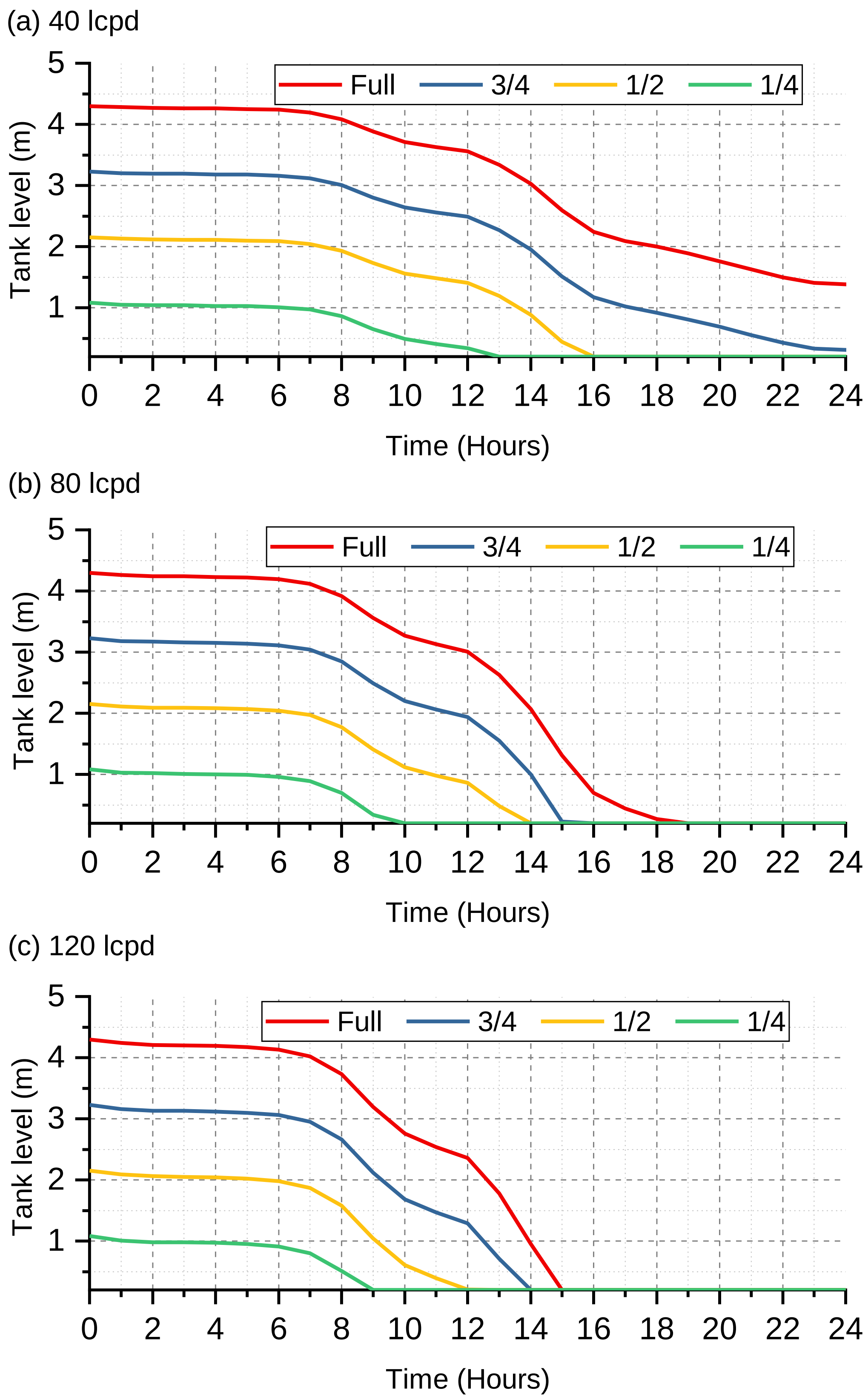



**Figure 6.17**: Tank level variation for demand pattern 1 (a) 40 lcpd (b) 80 lcpd (c) 120 lcpd

#### 6.6.3.2 Demand Pattern 2 results

Simulations for case 1 (40 lcpd), as can be seen in Figure 6.18(a), shows the effect of demand pattern 2 on the variation of water level in the tank. Even with maximum withdrawals at the start of supply, a full tank would be able sustain enough water level through 24 hours of supply with the water level at the end of supply period at 1.14 m. However, a significant reduction in possible supply hours was observed when initial tank level was decreased to 3/4 tank, where water level reaches minimum at 13 hours after start of supply. Similarly, initial tank levels at 1/2 and 1/4 will have the tank drain at hour 6 and hour 3 respectively. When compared with demand pattern 1 for initial tank levels at 1/2 and 1/4 adjusted for the nighttime low supply, the tank drains in 16 and 13 hours respectively. This shows that with demand pattern 2, lesser hours of supply would be achieved compared to demand pattern 1.

The results of case 2 (80 lcpd) show similar trends with case 1 as can be seen in Figure 6.18(b). There were sharp declines in water levels for all four initial tank levels. The times taken for each initial tank level to reach minimum were 8h, 6h 4h and 2h for Full tank, 3/4 tank, 1/2 tank and 1/4 tank respectively. It can clearly be observed that for demand pattern 2 and a per capita base demand of 80 lcpd, the system capacity would be insufficient and would not be able to satisfy the total system demand. In this scenario, the maximum withdrawal at the beginning greatly affect system performance.

Figure 6.18(c) shows the graph of Case 3 (120 lcpd) where various initial tank levels were tested. It was observed that with initial tank level at full tank, it would only take approximately 5 hours for the tank to completely drain. This may affect disadvantaged nodes in that some may not receive supply at all. Results for 3/4, 1/2 and 1/4 all show tank drain rates of less than 4 hours.

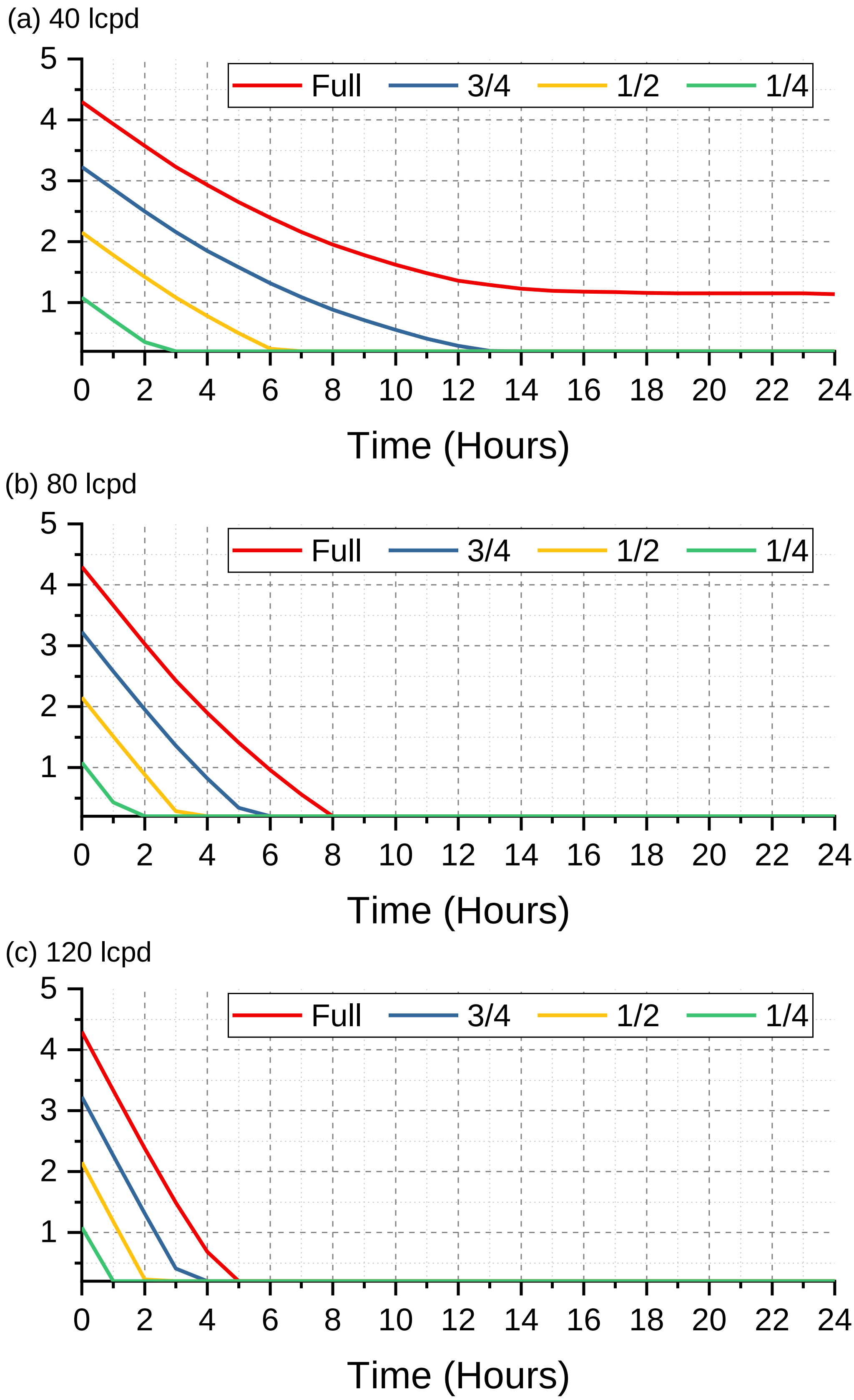



**Figure 6.18**: Tank level variation for demand pattern 2 (a) 40 lcpd (b) 80 lcpd (c) 120 lcpd

### 6.6.4 Summary

Demand driven analysis simulations were carried out to test the effect of different demand patterns on the distribution system performance, especially the tank drain rate. Of particular interest was the effect of high withdrawal rates at the beginning of supply as is reported to be common in systems operating intermittently.

Results show that the demand pattern 1 will likely provide longer hours of supply compared to Demand Pattern 2 where there is maximum withdrawal at the beginning of supply. A demand of 40lcpd in combination with Demand Pattern 1 shows the best possible result yielding highest pressure and longer tank drain rate. By contrast however, a demand of 120lcpd in combination with Demand Pattern 2 yields the lowest system pressure and shortest tank drain rate.

In situations like that of the case study model, analysis of pressure, supply duration and tank drain rate should be supported with other analyses to assess nodal demand satisfaction.

## 6.7 Engineering interventions for improved supply

### 6.7.1 Introduction

Results from the previous section have shown that although the network should be capable of providing a 24-hour supply, low pressures result in intermittent supply to the households. This has caused households to adopt water storage strategies as coping behaviours which changes the demand pattern. These actions in turn affect network performance as well as individual household supply, and leads to an overall increased consumption that the system can't deliver. Furthermore, evidence of the use of private pump stations by some households are very likely to further contribute to uneven demand across the network, and the weak performance and deterioration of the distribution system. It is therefore essential to consider options to improve the system performance, that would mitigate the likelihood of such coping behaviours. This will potentially enable a more equitable supply throughout the system as well as improved hours of supply.

Behavioural changes from the households need to be implemented so that there is minimal household interference in the performance of the distribution network. This would include the removal of private pumps and large storage tanks from households. However, to achieve these changes, it is first necessary for the utility company to implement engineering interventions to supply adequate water to the area with sufficient pressure and an appropriate strategy to provide 24-hour supply.

The following may be considered as engineering interventions that could improve levels of service to the case study distribution system:

1. More frequent filling of the tank to prevent the level dropping below the point where pressures in the network drop – This can be achieved by fixing the faulty boreholes and increasing frequency of refilling. However, this will result in higher energy demand from the utility company given the current interruptions in electricity supply and uncertainty in the availability of diesel to power the generators. Therefore, this intervention might not be feasible as it will lead to higher operating cost.
2. Increase source tank capacity (either replacing with a bigger tank or installing another one to increase the total volume) – This would increase volume of supply but as the elevation is still relatively low, there is likely to

be occurrence of low or negative pressure and consequently, disadvantaged nodes will still have less hours of supply than the advantaged nodes. This is likely to result in some storage behaviors to compensate for the IWS. Additionally, this option would increase operational costs for the utility as there will be an increase in the energy required to fill the tanks.

3. Installation of Pump Station to increase system pressure – This option would also increase pressure in the system. Although no major changes would be made within the distribution system, the use of pump stations requires electricity supply and given that electricity is one of the major factors hindering the supply of water to the case study area, alternative solutions which are sustainable should be considered.
4. Raising the elevation of the tank – this option is requires raising the elevation of the tank to a certain level that pressure becomes sufficient within the distribution system. It is a one-off intervention which guarantees improved pressure.

### 6.7.2 Raising Tank Elevation

Raising the tank elevation is likely to be the most effective engineering intervention to improve pressure without continuous reliance on electricity. This may result in positive economic returns. According a cost-benefit analysis by WHO, an investment of US$1 towards improving access to safe water would produce an economic return of US$3 – 34, depending on the region, while also achieving a 10% reduction in global diarrhea cases (WHO/UNICEF, 2005). Raising the elevation of the tank involves a one-off investment and would be ideal for regions like Jigawa State which are faced by economic water scarcity. There may be additional operating cost to fill the tank, which should be modest compared to other interventions.

An increase in tank elevation would increase the overall system pressure, reducing the impact of low pressure for disadvantaged nodes within the system and potentially increasing duration of supply to the nodes. It is essential however, to consider certain factors when raising the elevation of a tank. These include maximum and minimum required pressure as well as feasibility of raising the tank to the required level.

As discussed earlier in this thesis, the minimum required pressure for a distribution network varies by country. India has the lowest minimum pressure requirement of 7m hence, considering the water supply similarities between Nigeria and India, this value was adopted for the case study. It is intended that this pressure value should be met regardless of the level of water in the tank.

For a pressure of 7m to be maintained at the highest node in the distribution system of the case study area, the tank elevation must be raised 7.425m from the initial elevation of 431.5m to 438.925m. This new height will ensure that with water level in the tank at 1/4 full, pressure head of 7m would still be maintained at the highest nodes (i.e. elevation at 433m). For simulation purpose, 7.425m is rounded up to 8m and hence, a new base elevation of 439.5m will be used. This value was entered into EPANET and extended period simulations were run for different cases.

Figure 6.19 below shows a depiction of the location of the critical nodes in the distribution and their relative position to the main tank. These nodes (J18 and J29) can be considered as the control nodes in assessing the performance of the distribution system based on minimum and maximum pressure values obtained during the simulations.

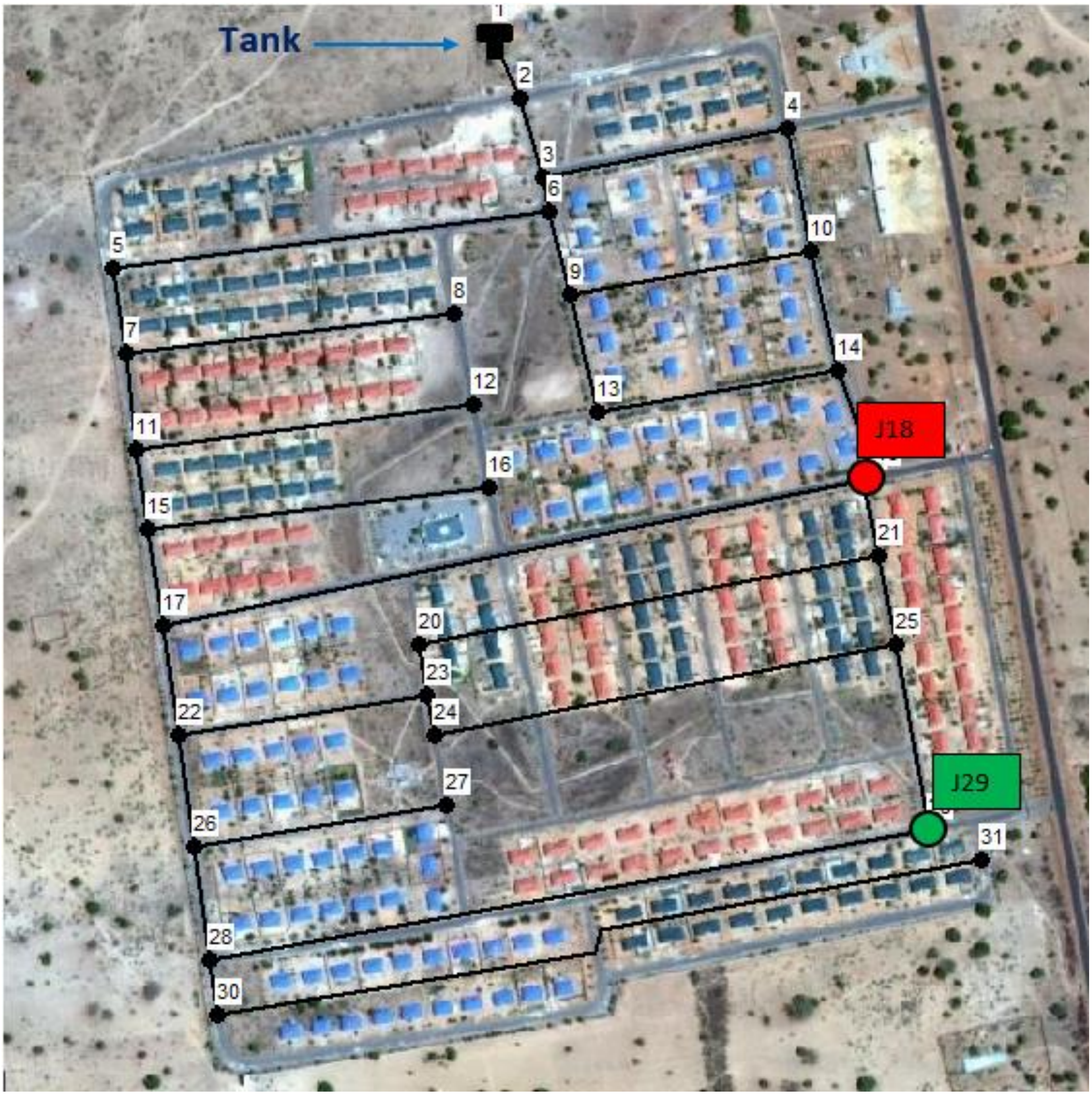



**Figure 6.19:** Location of critical nodes J18 and J29 in the case study network with respect to the main tank.

Node J18, having the highest elevation of 433m, can be used to ensure that minimum required pressure is supplied to that node. This implies that in a typical supply operation, all other nodes in the system will have pressure values greater than that of node J18. In a similar manner, node J29, having the lowest elevation of 427m in the system, can be used to determine the highest pressure within the system, thereby ensuring all other nodes do not have pressure values above the maximum required pressure.

### 6.7.3 Effect of tank elevation on pressure and supply hours

#### 6.7.3.1 Case 1 – Actual case study operation

Simulations were carried out to assess pressure and supply duration for the case study area. Even with the raised tank, results show that although 8 (eight) hours of supply is received, only a few nodes receive water for this duration. Figure 6.20 shows the pressure values and supply durations of selected nodes in the distribution network. For example, nodes J18 and J14 only receive approximately 3 hours and 6 hours respectively. Furthermore, the pressure head values for these nodes J18 and J14 were the lowest of all the nodal pressures in the distribution system, with values all falling below 2m.

On the other hand, nodes with lower elevations were found to have higher pressure values, hence resulting in longer duration of supply. Nodes J29 and J23 for example, were observed to have higher pressures which as a result, provides the nodes the full 8-hour supply. In total, of the 26 service nodes within the distribution system, only seven nodes have pressure above 2m at the end of the 8-hour supply while the remaining 21 nodes have pressure of less than 2m before the end of the 8-hour supply.

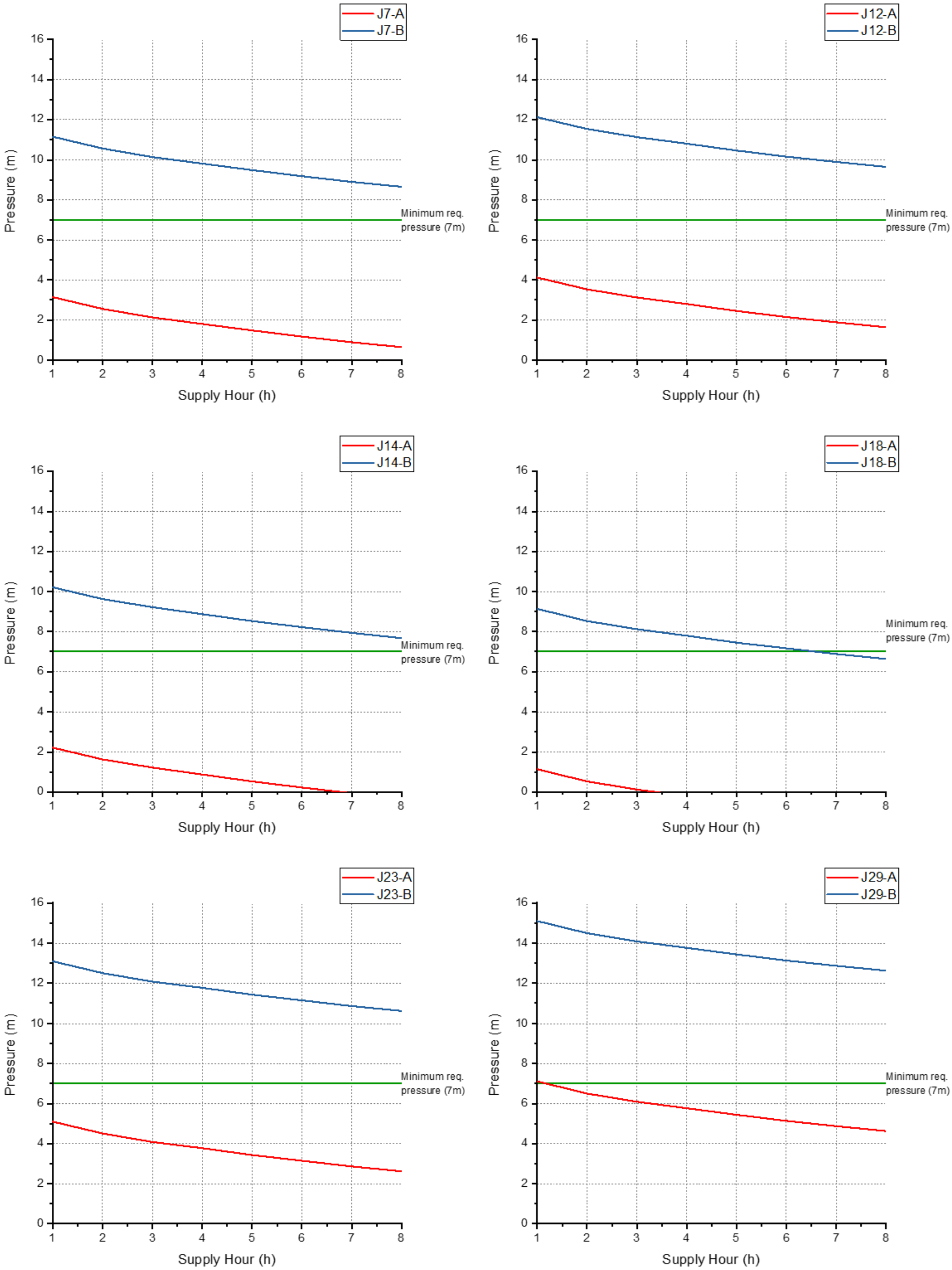



**Figure 6.20:** Pressure and supply durations of selected nodes for actual and modified tank elevations for the 8- hour supply scenario. (A = actual tank elevation (431.5m), B = modified tank elevation (439.5m)

On the contrary, simulation results have shown that raising the tank elevation by 8m will significantly improve the nodal pressure values as well as the supply duration to each node within the distribution network as can be seen in figure 6.20. For example, nodes J18 and 14, which initially had low pressure values, will now have the full 8 hours of supply with pressure values of approximately 7m and 8m respectfully at the end of supply. This means that in addition to having attain the 7m minimum pressure requirement, there will be a more equitable supply within the distribution system.

#### 6.7.3.2 Case 2 – Modified demand assuming constant consumption of 46lcpd

In this scenario, it was assumed that all household behaviour that significantly affects the performance of the system have been eliminated and a per capita consumption of 46lcpd is adopted by all households. It also represents the average consumption rate for Jigawa state, as previously mentioned in this thesis.

To evaluate the effect of tank elevation in this case, four simulations were also run. The first simulation was run assuming actual tank elevation of 431.5m while the second was run with the tank elevation raised 8m to 439.5m. Furthermore, these simulations assume the tank to be full at the start of simulation. Simulations were carried out for the two demand patterns earlier in this chapter (i.e. demand pattern 1 representing maximum consumption at the beginning of supply, and demand pattern 2 representing normal diurnal curve with two peaks during the day). Figure 6.21 shows a graphical representation of all the simulations carried out.

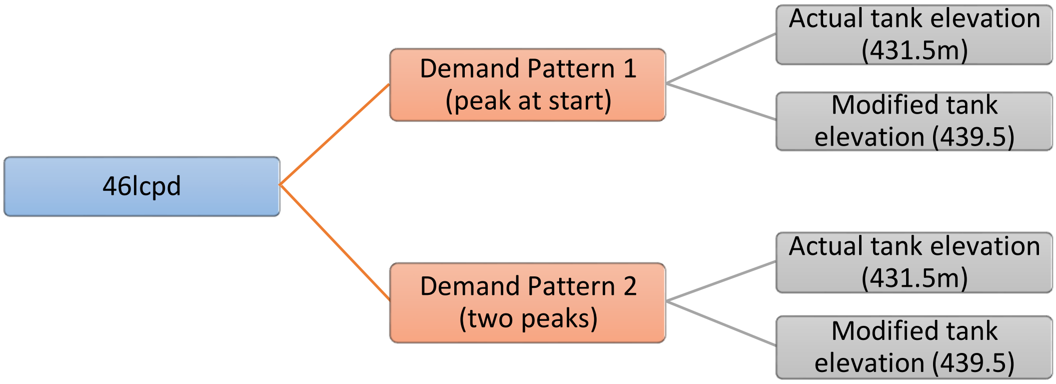



**Figure 6.21:** Description of simulations carried out for a uniform consumption of 46lcpd for both demand patterns using actual (431.5) and modified (439.5) tank elevations.

Simulation results in the previous sections have shown that at a per capita consumption of 46lcpd, the tank would be able to provide the system with 24 hours of supply, with a tank elevation at 431.5m. However, due to high elevations, some nodes will still have less than 24hours of supply even though there is enough water in the tank to satisfy the total system demand. Figure 6.22 shows pressure and supply durations for selected nodes considering actual and modified tank elevations. The purpose of these simulations is to explore the possibility of attaining 24-hour supply given that a demand of 46lcpd is maintained throughout the system.

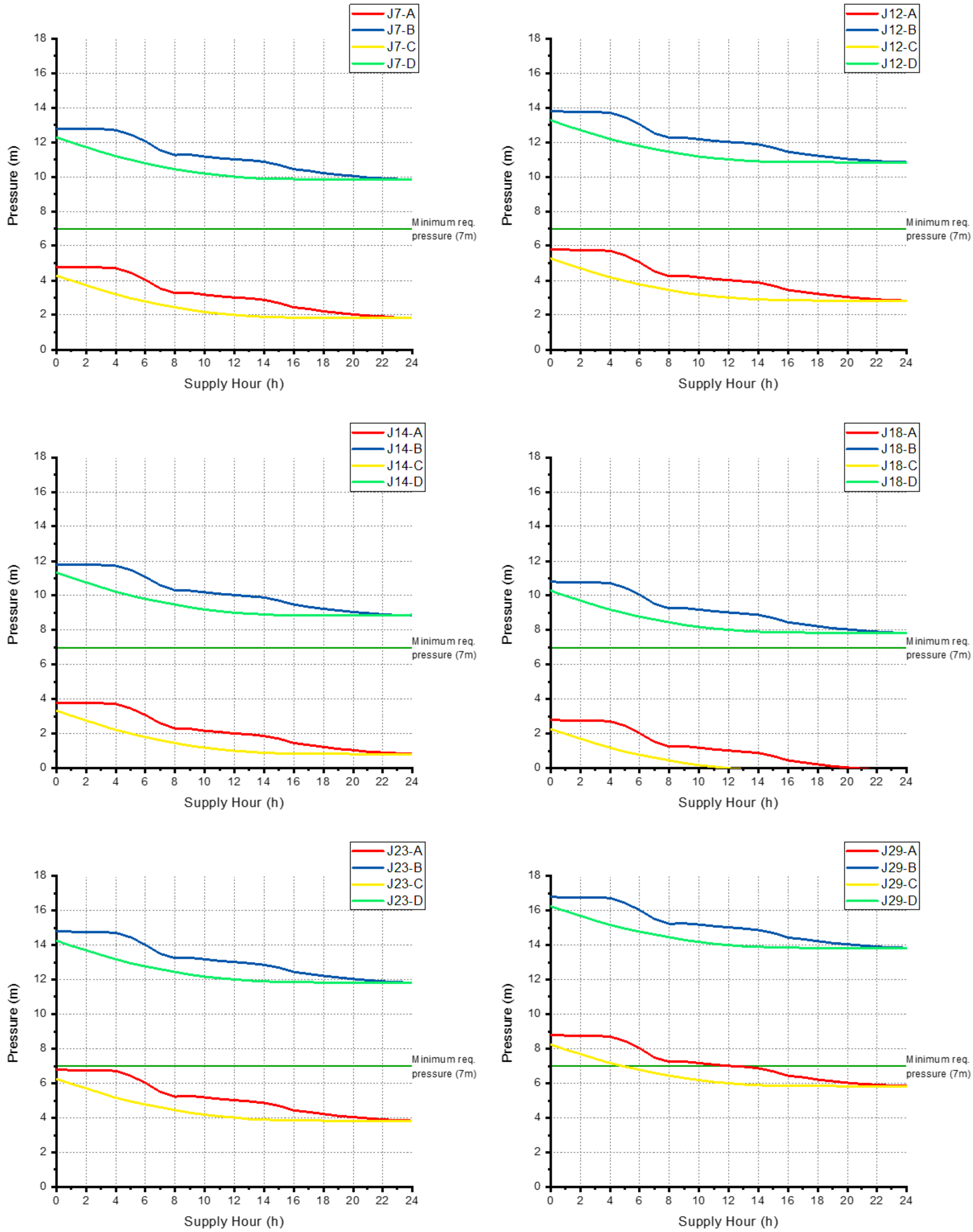



**Figure 6.22:** Pressure and supply durations of selected nodes for the 46lcpd supply scenario with actual and modified tank elevations for the different demand patterns. *(A =demand pattern 2, actual tank elevation (431.5m); B = demand pattern 2, modified tank elevation (439.5m); C = demand pattern 1, actual elevation; D = demand pattern 1, modified tan elevation).*

Simulation results show that for demand pattern 2 (two peaks), pressure at node J18 would be 0m after about 20 hours of supply while node J14 would have pressure value of less than 1m at the end of 24hours. These two nodes were found to have the lowest pressure values in the system, hence, resulting in lower hours of supply. Pressure values for nodes J29 and J23 were found to be highest with values ranging between 6m to 9m and 4m to 6m respectfully at the beginning and end of supply. The results for demand pattern 1 (peak at start) is found to be even worse where pressure values and supply durations tend to be lower than demand pattern 2. For example, node J18, which has the highest elevation, would receive a pressure of less than 3m and with supply duration lasting no more than 12 hours. This shows a difference of up to 6 hours of supply when compared with simulations using demand pattern 2 (two peak demand).

Overall, with tank elevation at 431.5m, majority of the nodes will receive 24-hour supply except for nodes J18. However, pressure values at all the nodes were found to be below the required minimum of 7m. Node J29, which has the highest pressure at the beginning of supply has its pressure drop below 7m at the end of supply.

On the other hand, simulation results show that raising the elevation of the tank has significant impact on the values of pressure and supply duration as can be seen in figure 6.22. All nodes were found to have sufficient pressure enough to provide 24hours of supply. For example, node J29 was found to have a maximum pressure of approximately 17m at the beginning of simulation and a minimum of approximately 14m at the end of 24 hours. Similarly, nodes J18 and J14, which are known to be the disadvantaged nodes due to their high elevation, were found to have maximum pressure values of approximately 11m and 12m respectively at the start of simulation, and a minimum pressure of approximately 8m and 9m respectively at the end of simulation.

## 6.8 Chapter summary

The modelling and simulation concepts discussed in chapter 5 were employed to simulate the operation and assess the performance of the WDN of the case study area based on data collected from the field work campaign. Results obtained were highlighted and the need to further test the model using different demand options was suggested.

Assumptions were made and a model set up to represent over consumption at some nodes. Results showed that pressure within nodes decreased as a result of over consumption. This was therefore concluded that overconsumption and over withdrawal should be avoided to promote equity in distribution. Suggestions were given on how it can be reduced and how system can be improved.

The model was tested by simulating various operating scenarios and the impact on the distribution network was discussed. Pressure variations across the system were observed and vulnerable regions were identified. The chapter concludes that the system is overstressed with higher consumption rates compared to local and national rates. The pressure results obtained are well below the minimum standard guidelines of 7m, making the network to be considered as deficient. The chapter also concluded that with reduced demands, the network would be able to perform better and provide more hours of supply than is currently being received. The possibility of raising the tank to provide minimum design pressure was explored and results have shown how raising the tank elevation by 8m significantly improves pressure across the system.

# Chapter 7: Pressure Dependent Analysis of the Case Study Area

## 7.1 Overview

This chapter introduces an alternative modelling approach using Pressure Driven Analysis (PDD). The governing equations and the software used to carry out the pressure driven demand (PDD) analysis of the case study network were presented. The chapter presents the results of a PDD analysis using WaterGems in an attempt to evaluate nodal demand shortfall within the case study network. Limitations of PDD analysis and its application to IWS are discussed.

## 7.2 Pressure Dependent Demand

### 7.2.1 Introduction

As mentioned in the previous chapters, there are cases where pressure within a distribution system can be affected by a number of reasons. One of such is the operation of intermittent water supply. This is evident in the case study of this thesis where operating intermittent water supply has resulted in not only a variation of pressure within nodes but having significantly low pressure across the system. This has proven that most nodes may not have been receiving the required pressure to satisfy the required nodal demand.

In such instances were pressure varies and becomes significantly low, nodal demand, which is the water available at a node, becomes dependent on the available pressure and is thus termed pressure driven demand or pressure dependent demand (PDD). In contrast to conventional methods of demand-driven analysis, where demand is not influenced by pressure, for PDD, demand becomes a function of pressure if the pressure goes below a certain threshold value. Usually, this demand is considered to be zero when the corresponding pressure becomes zero. To account for this dependence on pressure, mathematical formulations need to be employed in order to find solution for the PDD function.

### 7.2.2 Formulation of PDD function

Typically, PDD may be defined in one of two forms of pressure-demand functions. This are the power function and the piecewise curve or table. The power function can be represented as below:

$$\frac{Q_i^s}{Q_{ri}} = \begin{cases} 0 & H_i \leq 0 \\ \left(\frac{H_i}{H_{ri}}\right)^{\alpha} & 0 < H_i < H_t \\ \left(\frac{H_t}{H_{ri}}\right)^{\alpha} & H_i \geq H_t \end{cases}, \quad (6.1)$$

where $Q_i^s$ is the computed demand at node $i$; $Q_{ri}$ is the original demand $i$; $H_i$ denotes the computed pressure at node $i$; $H_{ri}$ describes the reference pressure that will fully satisfy the original demand; $H_t$ is the threshold pressure beyond which demand becomes independent of pressure at the node and $\alpha$ denotes the exponent of pressure-demand relationship.

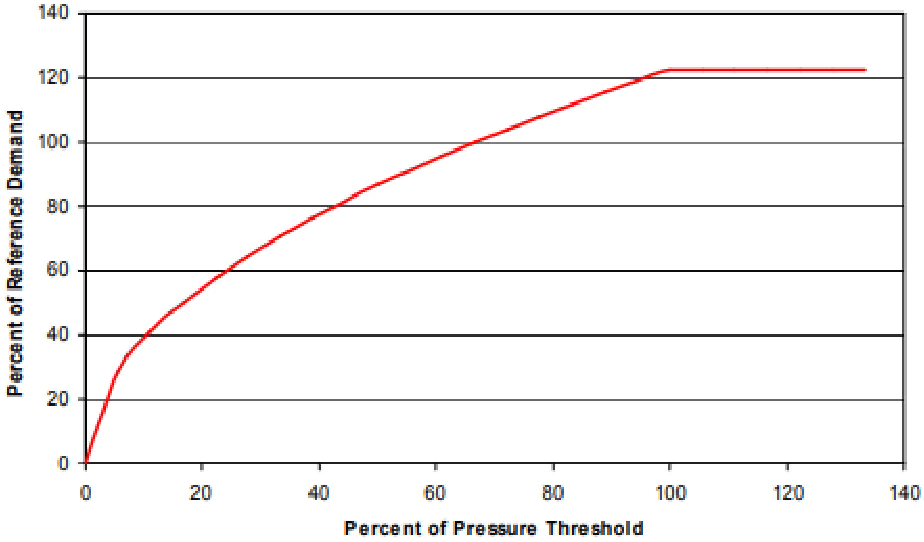



**Figure 7.1**: A typical pressure dependent demand curve (Source: Wu and Walski (2006))

In a typical PDD power function, as can be seen in Figure 7.1, the actual calculated demand rises with increase in pressure till it reaches 100% of the original required demand. This demand then remains constant once the pressure reaches or goes above the threshold pressure.

On the other hand, PDD function may also be represented as a piecewise table or a curve expressed as percentage pressure against percentage demand. Percentage pressure of a node is the ratio of actual nodal pressure to a threshold pressure whereas percentage demand is ratio of the computed nodal demand to the required demand. In PDD modelling and analysis method, it is assumed that the values of both pressure and demand at a node are unknown. This is contrary to conventional demand driven approach where demand at a node is known and fixed. For this reason therefore, the methodology algorithm for solving hydraulic model under PDD must be reformulated.

The following section describes the methodology for solving PDD hydraulic models.

### 7.2.3 Solution methodology for pressure dependent demand

The main approach is to use the conditions in equation 6.1 to solve pressure dependent demands. As mentioned earlier, nodal demand is a set value in conventional demand driven analyses. The solution to this analysis is obtained by applying the law of energy conservation and law of mass conservation respectively to each loop and each node. With this, a set of linear and quasi-nonlinear equations are iteratively solved to obtain the hydraulic solution of the network. Hence, a general formulation to solve demand driven network hydraulics is termed as the Global Gradient Algorithm (GGA) (Todini and Pilati, 1988). This can be represented by equation 6.2 below:

$$\begin{bmatrix} A_{11} & \dots & A_{12} \\ \dots & \dots & \dots \\ A_{21} & \dots & 0 \end{bmatrix} \begin{bmatrix} Q \\ \dots \\ H \end{bmatrix} = \begin{bmatrix} -A_{10}H_0 \\ \dots \\ -q \end{bmatrix}, \qquad (6.2)$$

where $Q$ is the unknown discharge from the pipe, $H$ is the unknown head at the node and $q$ is the set of demands at the node which are independent of the head $H_0$ at the node.

In pressure driven demand however, the value of demand is unknown, but it can be expressed as a function of pressure head at the node as described by equation 6.1. Thus, the solution matrix will be:

$$\begin{bmatrix} A_{11} & \dots & A_{12} \\ \dots & \dots & \dots \\ A_{21} & \dots & A_{22} \end{bmatrix} \begin{bmatrix} Q \\ \dots \\ H \end{bmatrix} = \begin{bmatrix} -A_{10}H_0 \\ \dots \\ -q \end{bmatrix}. \qquad (6.3)$$

Here, $A_{22}$ diagonal matrix is introduced into the solution matrix in equation 6.3. Thus, $A_{22}$ is a non-zero element and is expressed as:

$$A_{22}(i,i) = Q_i^s. \tag{6.4}$$

Another method exists that is usually employed to solve PDD as expressed in equation 6.3. This however depends on the supply characteristics that have been applied in equation 6.1. The formulation of PDD can be solved by employing the actual derivation of the global gradient algorithm as follows:

$$\begin{bmatrix} D_{11} & \dots & A_{12} \\ \dots & \dots & \dots \\ A_{21} & \dots & D_{22} \end{bmatrix} \begin{bmatrix} dQ \\ \dots \\ dH \end{bmatrix} = \begin{bmatrix} dE \\ \dots \\ dq \end{bmatrix}. \tag{6.5}$$

In this case, an alternative diagonal matrix $D_{22}$, is introduced in place of $A_{22}$ of pressure head $H$, from the global gradient algorithm. Taking this into consideration, the resulting expression for supply characteristics expressed in equation 6.1 therefore becomes:

$$D_{22}(i,i) = \begin{cases} 0 & H_i \leq 0 \\ \alpha \left(\frac{H_i}{H_t}\right)^{\alpha-1} \times Q_i & 0 < H_i < H_t\,. \\ 0 & H_i \geq H_t \end{cases} \tag{6.6}$$

This adjusted GGA therefore aims to compute $D_{22}$ for every node that is pressure dependent and include it into the expression of $A(i,i)$ as follows:

$$A(i,i) = \sum_j P_{ij} - D_{22}(i,i), \tag{6.7}$$

where $P_{ij}$ indicates the pipe $j$ which is connected to node $i$. The same notation is employed within the EPANET software formulation (Rossman, 2000).

## 7.3 Selection of PDD modelling software

### 7.3.1 Introduction

Pressure dependent demand (PDD) analysis has been discussed in detail in chapter 2, as well as in this chapter. Furthermore, advancement in the development of various hydraulic modelling software that have been used in literature for PDD analysis have also been discussed. Amongst these, one robust software, WaterGems (Bentley Systems Inc, 2017), has been used to demonstrate its capacity to model and analyse networks with deficient pressure (Walski et al., 2018, Wu and Walski, 2006, Wu et al., 2008b). Additionally, research has been carried out that verify the robustness and accuracy of the software in performing PDD analysis (Walski et al., 2017). The PDD model expressed above was incorporated and used as one of the main functionalities of WaterGems modelling software. This is in addition to a set of other PDD analysis data calculation options. This software was therefore selected in this thesis to harness its PDD modelling feature in assessing the water distribution network of the case study area. It should be noted however that up till the time of writing this thesis, no study has been found to have used PDD to assess the performance of a gravity fed water distribution systems with underperforming pressure whose source tank empties completely before another supply cycle. Therefore, this section attempts to use PDD function of WaterGems software to assess the performance of the case study water distribution network.

The following section describes WaterGems software, its capabilities and the advantages of using its PDD analysis feature.

### 7.3.2 WaterGems hydraulic modelling software

WaterGems is a robust software for hydraulic modelling of water distribution systems. It has been equipped with advanced features that enhances interoperability of the software for network optimisation through tools that support geospatial and asset management functionalities in model building and analysis. WaterGems is a versatile software that offers an extensive solutions for analysis of fire flow, water quality modelling as well as energy and cost management. Some of the key functionalities of the software are the pressure dependent demand analysis option, GIS and AutoCAD integration, optimisation of model calibration and criticality analysis. WaterGems has excellent interactive graphic user interface (GUI) with the ability to display multiple variation of results and graphs. These graphical tools include that for thematic mapping, colour-coding and symbology, ArcMap visualisation and contouring. Over the years, WaterGems has proven to be one of the most popular and robust hydraulic modelling and optimisation software with increasing number of users from both academia and industry (Sonaje and Joshi, 2015). The hydraulic solution algorithm employed by the software has been used by the likes of other software like EPANET 2 and has been known to be accurate in the calculation of hydraulic parameters for water distribution network models (Wu and Walski, 2006).

### 7.3.3 PDD Feature in WaterGems

One of the methods employed in modelling demands that vary with pressure is by setting the nodes to act as flow emitters. In this case the emitter property coefficient is assigned to the node (Cabrera-Bejar and Tzatchkov, 2009, Pathirana, 2010). Flow emitters are best used to model nodes that discharge water to the atmosphere like sprinklers or pipe breaks. As such, the approach does not put a cap on the amount of water used as pressure increases. Other pressure dependent demands however, especially water consumption, do not change once the pressure in the system reaches a certain threshold. Thus, in regions where system pressure is very high, the use of flow emitter tends to generate unrealistically high values of consumption. One more drawback for the use of flow emitters is that it computes demands to be negative once the corresponding nodal pressure is negative.

WaterGems PDD feature offers more robust control of the demand calculation. In various cases where water use is affected by pressure, the PDD feature will present more accurate and realistic result than only employing flow emitters on demand nodes.

The following are advantages of using the PDD feature:

- Ability to analyse pressure-dependent demands at individual nodes, a group of nodes, or all nodes.
- It gives the opportunity to set a reference pressure where 100 percent of the indicated reference demand can be achieved.
- It gives the opportunity to define a threshold pressure beyond which an increase in pressure results in no increase in demand.
- It gives the ability to merge both volume-based and PDD demands at separate nodes.
- Ability to identify the actual amount of water delivered to a pressure dependent demand node and the deficit in demand (also called shortfall).

- Allocating zero demands to nodes when residual pressure becomes zero or negative.
- Excellent versatility in presentation of computed PDD analysis results through graphs and tables.

Two formulations are employed by the software in solving pressure dependent demands based on the modified GGA methodology described earlier in this chapter. These formulations are the piecewise linear curve and the power function.

#### 7.3.3.1 Reference pressure

In order to carry out a PDD simulation, a reference pressure must be set. This is the pressure at which demands at a node are satisfied. It can also be defined as the typical pressure under typical demand conditions.

Typically, in most distribution system analyses, pressure tends to be almost similar at all the nodes and hence, that pressure can be set as global reference pressure for all nodes. However, when considering multiple nodes whose typical pressure vary significantly, there is then the need to over-ride the global reference pressure by assigning a separate pressure for each node.

To maximise the computed pressure dependent demand, a threshold pressure was set. Setting a threshold pressure allows demands to be constant once this threshold value has been exceeded. On the other hand, if a threshold pressure has not been set, demand will increase with increase in pressure regardless of its magnitude.

## 7.4 Simulation of the case study model

### 7.4.1 Introduction

One of the key functionalities of WaterGems is its ability to import EPANET file into its domain. This is simply achieved by importing .inp files from EPANET into the software and all other analysis can be carried out. This reduces the time it would take to rebuild a model that was constructed and analysed in EPANET.

The actual case study model developed and used in the previous chapter was therefore saved as a .inp file in EPANET and imported using WaterGems. Figure 7.2 shows the imported model in the WaterGems environment.

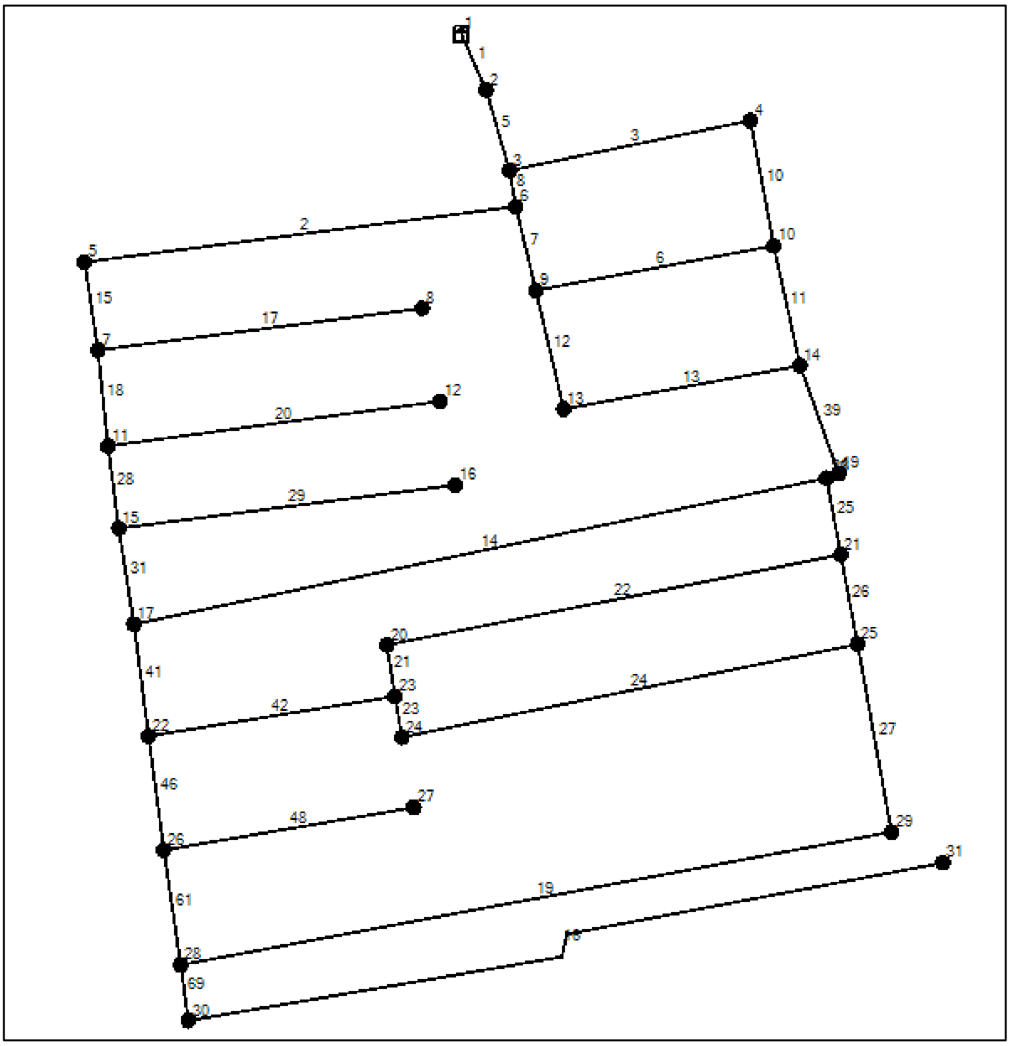



**Figure 7.2**: Imported model from EPANET

The image shows that the network setup is identical to that used in EPANET. All initial settings and conditions including baseline demands, demand patterns identification and symbology were equally imported.

### 7.4.2 Testing the model

Verification of the imported model was carried out by running simple steady state demand driven simulations. The results from the simulations was compared with that obtained using EPANET in the previous chapter. This is to ensure that all the element set up in the original model are in place and simulation results on both software are identical.

### 7.4.3 Setting up PDD

Setting up a PDD function requires creating a separate scenario into which the PDD alternative can be set up. This will provide a means through which comparisons can be made between a normal model and a PDD model.

The PDD scenario for the of the case study is referred to as TrueCasePDD while the normal non PDD scenario is termed TrueCase NoPDD.

Reference pressure for each node was the pressure values at the start of simulation. This is considered to be the highest pressure that can be observed at the nodes.

## 7.5 Simulation Results

Simulations were performed to evaluate the demand shortfall for the case study water distribution network. Results show a variation between the required demand and the actual flow supplied to individual nodes. Figure 7.3 shows the variation between required demand and actual supply at node J22.

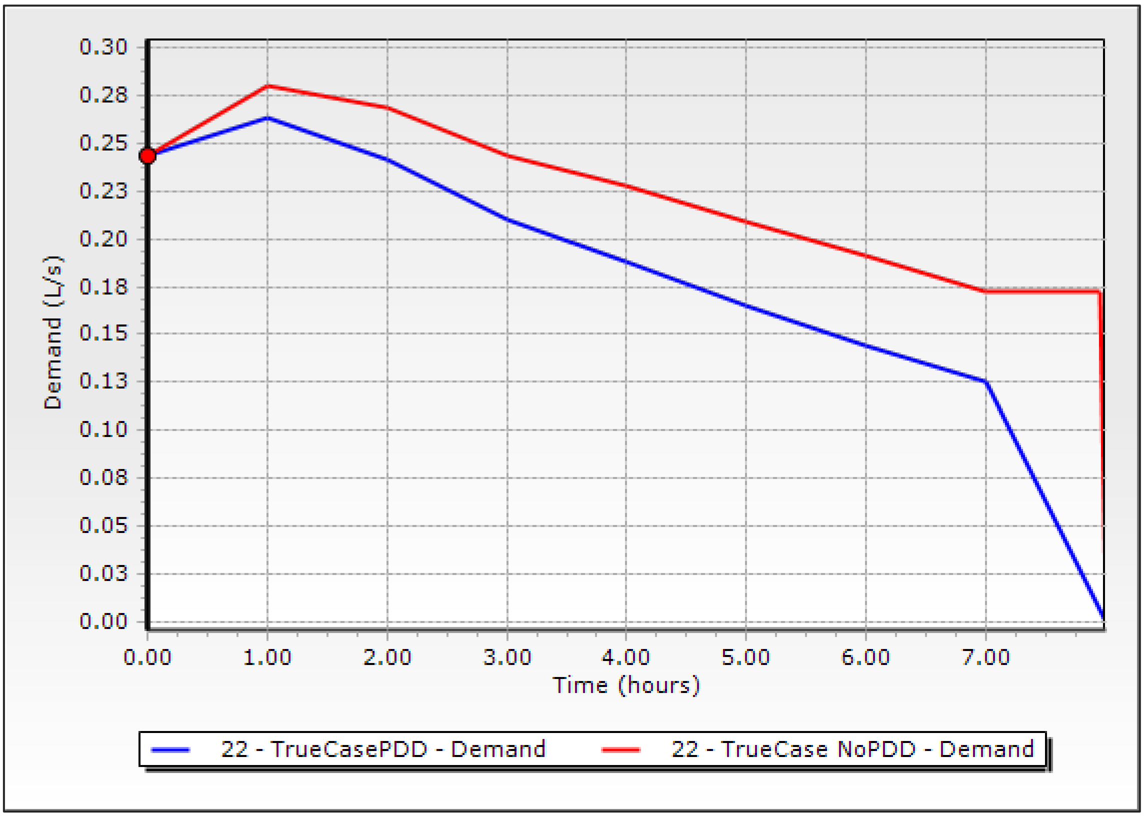



**Figure 7.3**: Actual demand versus supplied demand at node J22

From the graph it can be observed that the consumption follows the demand pattern set at the respective nodes. Actual flow at this node during the 8th hour of supply was observed to be 0.12 l/s instead of the required 0.17 l/s. This is an indication that the reduction in pressure actually has effect on supply to that node.

Disadvantaged nodes were observed to be more affected by the effect of low pressure. For example, Figure 7.4 shows the requested supplied demand with respect to available pressure at node 18.

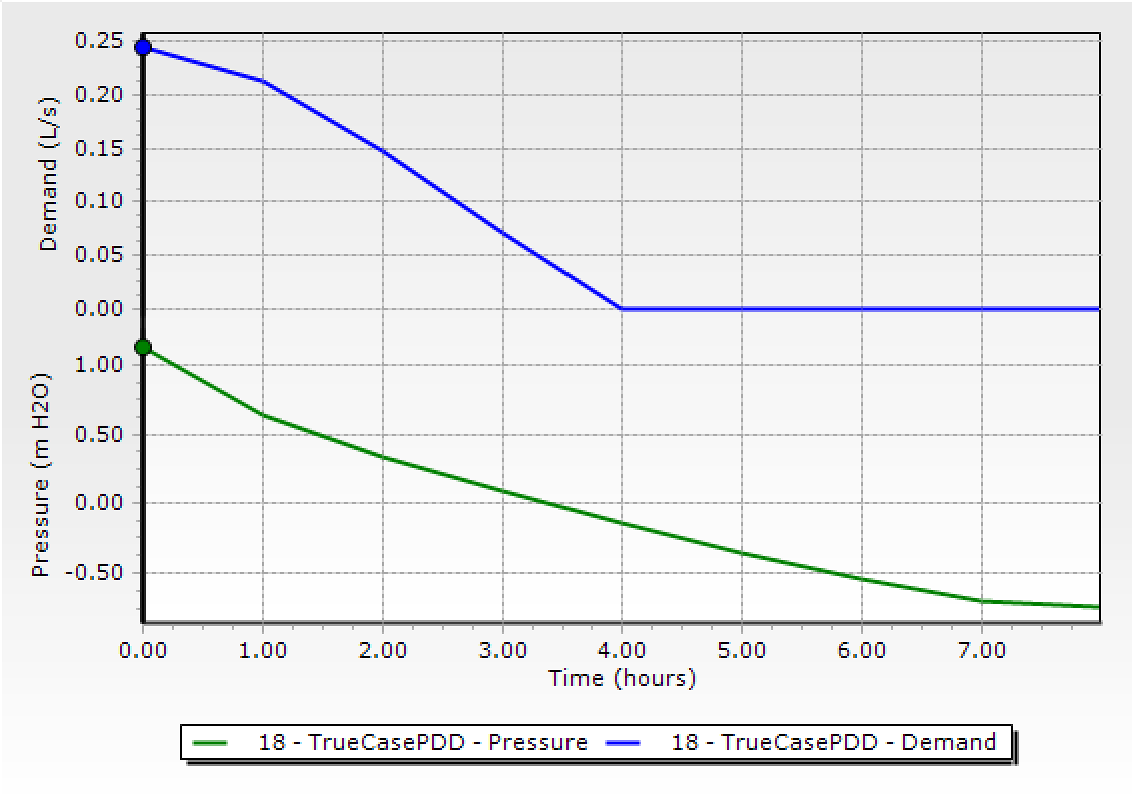



**Figure 7.4**: Pressure and actual supply values for node J18

The graph shows the effect of negative pressure on the node. With the node having the lowest pressure, at supply time of 3 hours where the pressure turns negative, the demand turns to zero. This is an indication that customers at this point will have no supply. Furthermore, Figure 7.5 shows the comparison between requested demand and actual demand at node J18.

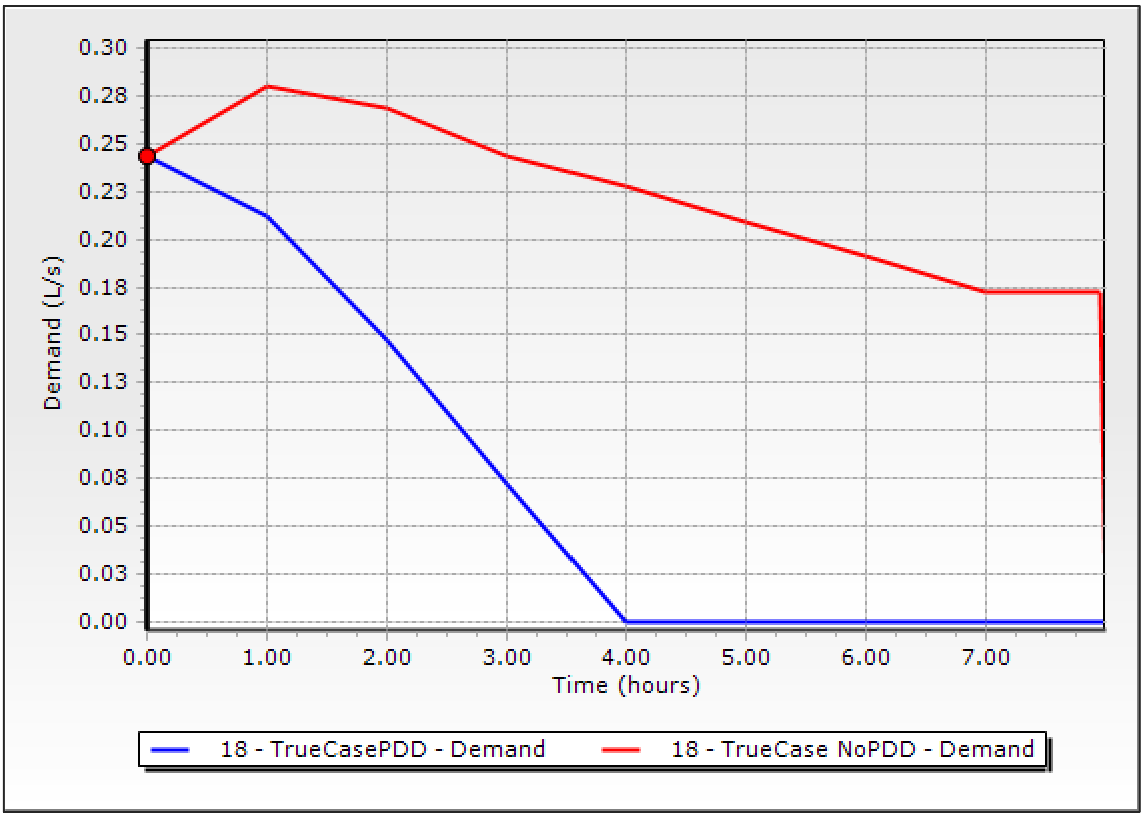



**Figure 7.5**: Actual demand versus supplied demand at node J18

From the graph above, the dependency of demand can clearly be identified as the actual supplied flow at the junction is observed to be much lower than the required demand. At hour 2 for example, only 55.5% of the required demand is being supplied to the node. This shows that customers on this node will be getting only half of the demand by the second hour of supply.

Results for node J29, as can be seen in Figure 7.6 show much less effects of lower pressure on actual supply.

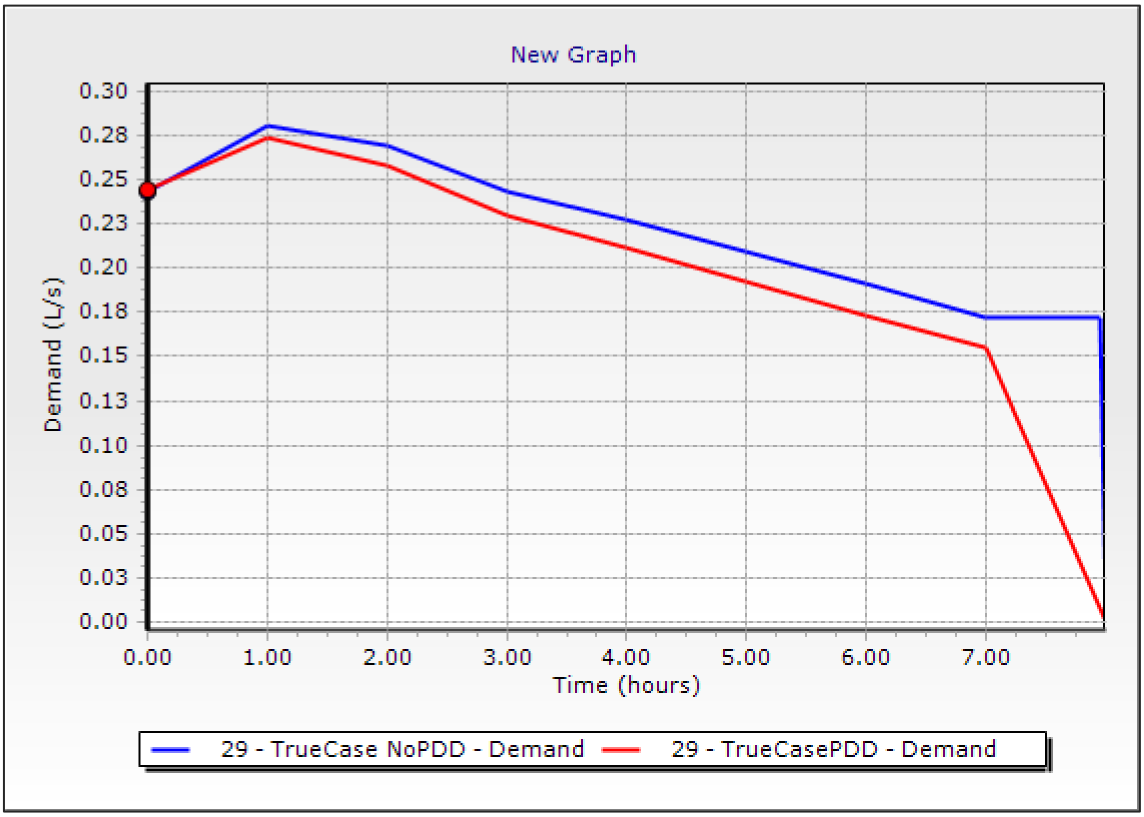



**Figure 7.6**: Required demand versus supplied demand at node J29

This node has the least variation if supply as it has the highest pressure in the network. The supplied demand at this node at the end of supply was found to be 0.15 l/s as against a required demand of 0.17 l/s.

## 7.6 Discussion and Conclusion

Pressure driven simulations were carried out on the case study WDN. Input parameters were the same as demand driven analysis performed in chapter 5. Results show that reduction in pressure significantly reduces the quantity of water being supplied to nodes. Because all nodes in the network have no fixed pressure, it can be concluded that in such systems, there is a multifaceted impact on supply of water to consumers. First, there is the constant reduction of pressure due to tank draining which may reduce available water and increase collection time and secondly, there may be the possibility of over withdrawal by some consumers. Similar results were found for all other nodes in the system where expected water supplied was less than the demand. This may be a challenge to consider in the PDD simulation of WDSs whose pressure reduces to zero. This is because typical PDD simulations consider the pressure in the system to be constant even if values are low. Therefore, there is a need to further investigate the mathematical solutions to PDD nodes whose pressure decreases to zero. Additionally, there is a need to consider tanks that drain completely as a common occurrence in low income countries, as have been proven in this case study. Despite this however, the use of WaterGems software in performing PDD analysis has provided an insight into the complexity of WDS that operate intermittently. This can inform stakeholders and water utilities on the negative impacts of IWS and the possible ways to tackle such anomaly.

One of the many ways to improve such system is to simply increase both capacity and head of the main tank. This would provide sufficient pressure in the system such that over withdrawal from certain households will have little impact on supply quantity of received by others. Another approach to solving the issue of over withdrawal is to enforce law that prohibit the use of private pump stations as well as large storage tanks by certain households. However, this might not be easily achievable as behavioural change may take longer durations to take effect.

# Chapter 8: General Discussions

## 8.1 Introduction

Access to safe and reliable quantities of water supply is crucial for health and wellbeing. Although many low- and middle-income countries have made significant progress towards extending access to water supply services, many countries have struggled to ensure that these are reliable and sustainable. Progress towards SDG 6 of the Sustainable Development Goals remains slow. Intermittency in piped water supply networks associated with poor management remains a dominant mode of service, particularly in poorer cities and towns, often presenting a more significant barrier to adequate water supplies compared, for example, with overall stress on water resources. Despite its importance there is a dearth of good quality research to describe or facilitate the analysis of the interactions between such intermittency and human behaviours.

The primary aim of this research is to develop new approaches to understand how poor system performance interacts with human behaviour in water supply networks under intermittent operating conditions. To do this both new and existing modelling approaches were combined with primary data collection from a case study town in Nigeria to address the following key questions:

- How do households respond to intermittent water supply?
    - What coping strategies do households adopt and how are these impacted by the nature of the intermittency experienced?
- How do these responses interact with the performance of the distribution network?

- How well can modified network models predict the outcomes of intermittent supply and the associated household behaviours?
    - How do typical networks (for example in small systems in Northern Nigeria) perform under intermittent supply?
    - What consumption patterns do households produce as a result of network performance coupled with their coping strategies?
    - How do the household level modifications and behavioural responses affect system performance?
- Can Engineering interventions improve service delivery in a typical case study?

This thesis offers new insight into household coping strategies in response to intermittent water supply. The research is practice-facing, proposing solutions to the economic water scarcity faced by communities in peri-urban Nigeria.

Key results and findings of the thesis have been presented within individual results chapters as follows: Household coping strategies (Chapter 4); Capacity assessment of case study distribution network (Chapter 5); Analysis of case study model and introduction of engineering interventions (Chapter 6 and 7).

This chapter discusses in broader details, the key findings reported from these chapters.

## 8.2 Household response to Intermittent Water Supplies

### 8.2.1 Introduction

The majority of the households in the case study area have significantly low hours of supply, despite the fact that the system overall is operational for 16 hours per day. There is a high level of inequality in duration of supply across the system. Many households reported low pressure supply and most experiencing less than the maximum 16 hours of supply. Responses to the poor quality of the supply varied across the network and were related to wealth and household size. There was significant evidence that coping strategies had a knock-on effect, lowering the pressure and availability of water to downstream households in almost all cases.

### 8.2.2 Storage

The most common and most important response among households who receive intermittent water supply is storing water in containers to cater for their needs when there is no supply.  This backs up findings from earlier studies (Choe et al., 1996, Gulyani et al., 2005, Klingel, 2012, Rosenberg et al., 2008, Zuin et al., 2011). About 90% percent of households in Abuja (Abubakar, 2018), 46% in Ogun, (Adeniji-Oloukoi et al., 2013) and 26% in Makurdi, Nigeria (Ahile et al., 2015) use water from a variety of storage containers. Similarly, up to 63% of households in Delhi, India (Zérah, 2000) also stored water in containers. The use of storage containers may help reduce turbidity, as suspended particles settle down over time, but is also associated with increased levels of microbial contamination, and is generally not recommended in dense settlements or where sanitary and hygiene conditions are sub optimal.

Most households in the case study area (93%) were storing water for use when the supply is unavailable. Various types of storage facilities were identified but large outdoor storage tanks were common and are likely to have a significant impact on the network operation. They may encourage overdraw (Lee and Schwab, 2005, Vairavamoorthy et al., 2008), wastage (Batish, 2003, Zérah,

2000) and possible contamination (Evison and Sunna, 2001, Tokajian and Hashwa, 2003).

The regular use of such storage tanks poses a serious challenge to modellers as there would be the need to consider overdraw in modelling. While this may be considered as a type of demand pattern since users try to fill up their tanks when supply is switched on for a specified period, there has been little work done to establish the validity of the techniques.

While water treatment, which includes filtration, chlorination, boiling and the use of Alum are often said to be widely used where there are high rates of water storage, in this case study only one household reported the use of in-line filters to purify water. Other households reported boiling water before drinking. This is unsurprising as there is a widespread assumption that the water in the network is equivalent to water from boreholes. The latter is usually considered clean and safe for consumption in Nigeria. Tragically, this is unlikely to be true since the risk of contamination is extremely high due to the repeated negative pressures and potential inward contamination in the network, contamination in the header tank which is extremely poorly maintained, and contamination associated with household stored water. The latter is widely reported in studies (Agensi et al., 2019, Heitzinger et al., 2015), All of these factors suggest that water should be treated before consumption.

With regards to water use, average consumption in the case study households was 46 litres per capita per day. This corresponds with the average consumption of Jigawa state as reported in literature. However, the wide range of reported supply hours and observations of household behavior suggest that actual consumption varies very widely. Many households are likely to be consuming significantly less than is generally recommended, while in other households there was evidence of high levels of non-essential use (including washing cars for example) and wastage. The disparity in supply hours, per capita consumption and storage volumes are an illustration of the wide-ranging impacts of IWS on quality of service.

While storing water can be associated with increased risk of contamination and poor health outcomes, in the case study area, stored water was primarily used for non-consumption purposes – primarily household chores, even though indoor taps and faucets were present in kitchens and bathrooms in all the surveyed households. Stored water was also used for flushing toilets, some cooking and general hygiene. Unless a house has an overhead tank, which feeds the house when supply is switched off, households use water in containers stored in the toilets to flush. The same applies for cooking, dish washing and laundry. In fact, the primary purpose of the taps in most of the households was only to collect and store water when there is supply.

The use of large household storage tanks is likely to increase the demand on the network whenever water is available, hence further contributing to the intermittency in supply. Moreover, the time it will take to fill up these tanks will have direct effect on the supply duration of neighbouring households. Studies have found that such storage of water may encourage households to overdraw water from the system (Batish, 2003, Coelho et al., 2003, Ingeduld et al., 2006, Lee and Schwab, 2005). One suggestion of controlling this overdraw may be to limit the amount of water that can be withdrawn by a household in a day. This could be achieved by installing flow restrictors on the pipes that connect to the households. As an alternative, public information and/or behaviour change strategies could be employed to influence or encourage households to reduce their consumption and subsequent waste of water, although there is limited evidence that these can be effective given the poor quality of the service. Furthermore, given the shortage of staff for even basic network operation, an intensive behaviour change intervention which would have high staffing inputs, seems implausible.

### 8.2.3 Use of private pump stations

One of the most detrimental coping mechanisms adopted by households is the use of private pumps to extract water from the network when it is running at low pressure. With more than one-third (36%) of the households having private electric pumps, the impact that this may have on the distribution network will be significant. Connecting a pump to the distribution mains will have serious effect on the performance of the distribution network leading to increased inequity in supply to households. One respondent said:

"*Whenever supply is switched on, my neighbour switches on his electric pump. As a result, I do not receive water till he has filled up all his storage containers. After he has switched off his pump, I only receive water for a few minutes before the Water Board switches off the supply."*

This attitude has been shown to have direct influence on other users. The inherent low pressure in the system makes it particularly vulnerable to the effect of pumps. If the pressure were high enough, then the use of pumps would have had little or no effect on the system. If adequate water were supplied at reasonable pressure, then pumping would cease. Until that situation is achieved, the utility could only reduce pump usage through regulation – and as mentioned above this seems unlikely to be feasible with low staffing levels and capacity.

The decision to adopt any coping strategy by households may be influenced by one or more factors. Need for water, cost of adopted strategy, socio-economic factors and frequency and quantity of water supply have been identified as factors that greatly influence household's preference for choice of coping strategy (Abubakar, 2018, Majuru et al., 2016). In this study, the choice of strategy was largely influenced by the amount of water received by individual households, the supply hours and the water pressure. Every household needs water to survive and people will go to any length to obtain water irrespective of the impact these strategies have on the water distribution system or on other users. In view of this, it is essential that both engineering and behavioural interventions be considered to ensure service delivery is improved and consumption controlled.

## 8.3 Assessment of case study distribution network

An appraisal of the capacity of the case study distribution network was carried out and is summarised in chapter 5 of this thesis. The total volume of water the tank can accommodate is 184,700 litres in one filling. If the tank is refilled twice a day it will provide up to 369,400 litres per day. The typical consumption in this region of Nigeria is estimated at 46.22 lcpd (IBNET, 2014). With the average number of households at 6.7 persons (Chapter 4), it implies that total demand for the case study area would be approximately 156,385 litres per day. This indicates that even one supply cycle will be enough to satisfy the daily total demand. This remains one of the most important findings of this study at the local level – the system has the capacity to provide adequate water for every household – the existence of intermittency, and low consumption in some parts of the network is a function of poor management rather than water resource constraints. It seems plausible that this may often be the case in apparently water-stressed distribution networks such as this one.

In general, the presence of IWS and reports of insufficient water supply may possibly be attributed to factors such as mode of operation of the network (leading customers complaining of low pressure), over-withdrawal by some households (because of the presence of pumps and large storage tanks) and losses (IBNET, 2014, Kumpel, 2013, Tokajian and Hashwa, 2003, Totsuka et al., 2004, Tzatchkov and Cabrera-Bejar, 2009). Unsurprisingly, the results from this study also suggests similar factors which perfectly agree with studies that have reported these factors to be linked with the operation IWS. What is less clear is the history of adoption of these coping mechanisms – one area of important consideration is the potential to avoid entering into the spiral of intermittent operation and coping mechanisms through strong system management from the start.

One of the coping mechanisms adopted by households as discussed earlier in this thesis is the use of private pumps by households. The problem with installation of pumps is twofold – in the short (immediate) term, it sucks water out of the system so there is less water, in the medium term, it damages the pipes due to the dynamic changes in pressure, which causes splits and joint failure. This may result in leakage and consequently water shortage. The challenge here is that use of pumps is an unpredictable user behaviour which cannot be distinctively modelled accurately. Therefore, special considerations and assumptions may have to be made in order to have a fair representation of these kind of systems.

### 8.3.1 Network performance

In order to understand how the network performs under the influence of user behaviour as a result of IWS, Chapter 6 presented some scenarios tested to represent the various conditions to which the network may be subjected.

Tests on the system performance was carried out using EPANET for both steady-state and extended period simulations. Results immediately indicated a deficiency in the network. At some nodes, very low to sometimes negative pressure resulted from runs which simulated normal operational conditions. Other nodes within the system sustain relatively high pressure throughout the duration of supply. Given the nature of the study area where all households are bungalows and with no storey buildings, a pressure above 2 to 3 m may be expected to supply customers with reasonable flow to enable them to collect some water in their containers throughout the period of supply. These ‘high pressure’ nodes are therefore further evidence of inefficient operation of the network.

By contrast, where pressures are low, nodes and hence households are clearly disadvantaged. Clearly, it becomes pertinent to consider alternative interventions to reduce the effect of inequity within the distribution system. An alternative commonly proffered in literature to tackle overconsumption is demand management (DWAF, 2004, Butler and Memon, 2005). Examples of such alternatives are flow restrictors, pressure reducing valve, use of residential water meters and introduction of tariff plans. Again, as mentioned above, such interventions seem to lie outside the capacity of the current operators of the system.

### 8.3.2 Overdraw during supply hours

One of the key findings in this thesis was the consumption pattern of households when supply is switched on. Results from fieldwork indicated that maximum withdrawal of water was observed during the first hours from start of supply. These findings are in line with previous research (De Marchis et al., 2010). Furthermore, results from Chapter 4 (Household survey) showed how certain households had private pump stations and unnecessarily large storage tanks. The presence of these naturally suggests these households may overdraw water especially at the start of supply and consequently affect pressure as well as supply duration for other disadvantaged households.

Results from Chapter 6 demonstrates how these behaviours affect system performance. The possibility of overconsumption was tested by adjusting the assumptions about household behaviour. This results in a reduction of up to 25% in pressure across the network as a result of certain nodes withdrawing their full requirement in a very short duration. This indicates how a typical use of a booster pump by certain households affects the performance of the system, which in the long run, shortens the supply duration of other nodes and causing inequity in distribution. Several studies have mentioned how inequity in water supply is associated with IWS (Mokssit et al., 2018, Guragai et al., 2017, De Marchis et al., 2010, De Marchis et al., 2009, Klingel, 2012) but none have provided evidence of how the association between user behaviour and network performance leads to this inequity. The findings from these simulations can henceforth be used to present technical evidence as to why IWS systems are associated with inequity in supply.

Evidence from the simulation results suggests that there is a need to have a system where overconsumption can be significantly reduced or better still, eliminated. This can be achieved by increasing the capacity of the network or by using pumps at strategic locations in the system to increase the pressure. Other behavioural changes may also need to be enforced. For example, results findings from this research highlights why households should not be allowed to use private pumps let alone connected directly to the distribution mains. However, this can only be achieved if the system itself has been upgraded and households have built confidence in the mode of operation of the system.

### 8.3.3 Consumption pattern and tank drain rate

Demand driven analysis simulations were carried out to test the effect of different demand patterns on the distribution system performance, especially the tank drain rate. Of interest was the effect of high withdrawal rates at the beginning of supply as is reported to be common in systems operating intermittently. This was represented by demand pattern 2 (peak at start), where maximum withdrawal is considered at the start of the simulation run. Given the current capacity of the tank, results show that 46 lpcd could theoretically be supplied to all consumers. However, under several of the plausible demand patterns, and when initial tank levels were below the maximum, even this level of supply could not always be maintained.

The model showed how such a system, served by a single tank, is highly sensitive to per capita consumption and demand pattern, both of which are influenced by user behaviour. If the tank was constantly full, or being served by a continuous source, the pressure as well as the tank drain rate would not be significantly affected by the consumption pattern from the end user.

There was occurrence of low and negative pressure across system with some disadvantaged nodes clearly identified. Demand management options to control the consumption rates could provide a more equitable supply. Doing this will not only produce reasonable pressure across the system but may also extend the duration of supply given the tank capacity and hence serve as an improvement intervention to IWS systems.

## 8.4 Improving Service Delivery – Raising Tank Elevation

Several engineering interventions in the network infrastructure were examined. These included increasing tank capacity, installation of electric pumps, frequent or continuous refilling of the tank, and raising current tank elevation. Additionally, other behavioural changes from households to reduce overconsumption were evaluated. However, as with human nature, households may only be able to change their behaviour after an improvement in the levels of service have been observed. For instance, there may not be a need for the use of private pump stations and large storage tanks if users are confident they will get water at any time of the day when they switch on their taps. This will reduce the negative impressions that households have on the reliability of the system. For this reason, it would be preferable to first provide engineering interventions that will improve the confidence of the households on the system.

Simulations were carried out to assess the effect of raising the tank elevation, with the aim of improving hours of service. This intervention is the most appealing, since it requires a “one-off” intervention with the lowest lifecycle cost of operation to the utility company after installation. All other interventions would generate additional operating costs which, given the scarcity of resources and the uncertainty in electricity and diesel supply, may not be viable.

A raised tank would provide and maintain up to 7m of pressure across all nodes in the distribution system. This means that during the supply cycle, all nodes will receive equitable supply. Households would therefore not have to complain of insufficient pressure as well as fewer hours of supply. However, while households within the system continue to have access to private pump stations while others have large storage tanks, the possibility of overconsumption and wastage of water remains.

To test the significance of this possibility a second scenario was tested, eliminating the extreme user behavior (over consumption through the use of pumps and large storage tanks) and limiting per capita consumption to 46lcpd (equivalent to the current average household storage capacity, and reflecting the average consumption for Jigawa State). With this set up, and raised tank elevation, 24-hour supply can easily be achieved, with pressure values staying well above the minimum requirement across all nodes. The results in this simulation can be used by the utility company in deciding what step to take in controlling user overconsumption through use of private pump stations and large storage tanks.

## 8.5 Key Takeaways

This research has scrutinized a water distribution system of a case study area which provides intermittent form of water supply and four key takeaways have been identified.

**IWS in this case is not a function of water scarcity but of poor management.**

The first key takeaway is that the intermittent water supply experienced in the case study is not a function of physical water scarcity but a function of economic water scarcity. As shown in chapter 6, the network as it stands, does not have the potential to deliver quality of service for which it was designed. However, since the absolute quantity of water available is sufficient for the user needs in the area, the system could be re-engineered using some basic practical modifications; a combination of engineering interventions as well as good management.

**Users will respond to poor quality service because water is important to them.**

The second takeaway is that, faced with poor quality service, people rationally invest in coping strategies. Although there is a tendency to view these strategies as ‘bad behaviour’, they are simply a logical response from consumers who have a high level of motivation to get the water they need. The behaviours can be said to be “forced” as a result of the poor quality of service provided. Consumers reported a high desire for continuous supply, but more importantly they had invested significant money in coping strategies. This suggests that there is headroom to raise water tariffs, provided these are associated with a higher level of service.

**New modelling tools are needed to better understand the interaction between intermittency and household behavior.**

Third, in trying to understand the problem of intermittency, EPANET and WaterGems are currently inadequate or at best inefficient at capturing the interaction between intermittent supply and household behaviour. This presents a big challenge and hence, more work is needed to develop standard approaches for modelling and testing out ways of improving these types of networks. There are currently so many similar distribution networks around the world. Therefore, a specifically designed tool to test how such networks perform under intermittency can be used to carry out significant research as is demonstrated in this thesis.

The current boom in the development of satellite housing schemes with their associated decentralised tank and network water supplies in Nigeria (Abubakar and Doan, 2017, Kester, 2014), is mirrored in many regions of the world. Furthermore, IWS dominates network supplies in many places, and sadly, due to low levels of human capacity and inadequate attention to operational management, it is likely to be in existence globally for years to come. The novel approach presented in this thesis, of using a modified demand pattern (i.e. Maximum withdrawal at start of supply) to predict actual operational performance of the network, could be more widely used by modellers to generate a better understanding of the performance of distribution networks under intermittent supply.

**Water Projects are at risk of slipping into a downward spiral of poor performance without adequate attention to operations and maintenance.**

The final takeaway is that the problems of IWS tends to be presented by policy makers as a problem of perverse behavior by individuals. However, people need water and they would do anything to get it when they have very poor levels of service. Thus, it seems plausible from this study that if the system had been designed properly from the beginning, and if it had been operated 24/7 at reasonable pressure, consumers would probably never have invested in the coping behaviour. Therefore, the real key is to have an active and properly funded operations and maintenance. This would prevent the system from slipping into the negative downward spiral of IWS.

# Chapter 9: Conclusions

## 9.1 Chapter introduction

This chapter presents overall conclusions of this thesis based on the aims and objectives set out in chapter one. Limitations of the study are also presented in this chapter. The chapter also discusses the application of the research findings and concludes with recommendations for further research.

## 9.2 Research conclusions

The main aim of this research is to develop new approaches to understand how human behaviour and system performance interact in Intermittent Water Supply systems. The research focused on a case study water distribution network in Jigawa State, Nigeria.

A review of literature has shown that addressing IWS is a complex task and concludes that there is a need to further investigate the multifaceted interrelation between mode of operation of IWS and the consequence of user behaviour response. There is also a need to make sure water utilities are properly managed as to avoid systems falling into the downward spiral of intermittent water supply.

Results from household survey suggests that customers receive intermittent supply with supply duration varying greatly across the estate although the water company claims longer hours. Customers have adopted coping strategies in response to the intermittency and results show that the most common strategy is the use of some form of storage container to store water for use when there is no supply. Direct connection of private pumps by some households have been found to be one of the possible causes of the deterioration of the supply service. This, coupled with large storage tanks may result in overconsumption and waste, which exacerbates water shortage, making it also challenging for modellers to simulate such behaviours. The study concludes that the network is underperforming considering the deficiencies in water sources to the tank and others like electricity and diesel for the backup generators resulting in low pressure across the system. This research also demonstrated how the of private pumps deteriorates the network and measures need to be taken to enforce users not to use pumps.

A hydraulic appraisal of the water distribution system source tank capacity was carried out using field data and showed that given normal per capita demand of this region of the country, the tank would have been able to satisfy that demand. However, the study concluded that the mode of system operation and poor management has contributed to users' distrust in the system, causing them to put in pumps and tanks. The study also concludes that the use of such pumps is most likely the most detrimental of all the coping behaviours which may have serious consequences in the pressure levels across the distribution system.

The use of hydraulic modelling tools to carry out both demand driven and demand dependent analysis of the network have shown the effects of overconsumption in IWS systems which exhibit lower than standard level of pressure across the system. Pressure values and nodal supply durations have been shown to be greatly influenced by nodal overconsumption/overdraw. The research concludes that lower level of pressure in the system makes it more sensitive as well as vulnerable to changes in withdrawal rates. This suggests that higher pressures would greatly reduce inequity in distribution and would reduce the effect caused by some users on the distribution system. The study also concludes that lower pressure distribution systems, especially those having source tank that completely empties, poses some mathematical challenges in pressure driven analysis as it does not provide a reasonable justification for the selection of reference pressure.

The study further concluded that water distribution systems which provide intermittent water supply and having low system pressure are bound to cause users to adopt extreme coping behaviours like the use of private pumps. To avoid such behaviour, the system must be made to provide higher pressures enough to reduce the impact of overconsumption on other nodes across the system. Simulations carried out have proven that an increase in tank height will significantly increase pressure as well as supply durations, consequently reducing inequity in supply and producing better levels of service. Infrastructural improvements in the case study area would also improve service delivery and reduce the effect of economic water scarcity.

Although there is no straightforward approach to solving IWS, the best way to stop the effects of inequality in water supply and help countries achieve SDG 6 is to convert IWS to continuous supply. There is a need to explore stories of ‘failed’ water systems in more detail to understand why they fail and how they could be managed better.

## 9.3 Limitations of study

This research was made in an attempt to explore intermittent water supply and its effects on both user behaviour and network performance for a case study water distribution system in Nigeria. It gives an important perspective of user behaviour and performance of intermittent systems with particularly low pressure. Despite this, some limitations have been recognised.

The first limitation is the sample size for the household survey. The initial sample size was not achieved due to time and financial constraints and the time at which respondents were available for interview. However, the responses were obtained believed to be representative of the typical behaviour of households within the study community.

Secondly, the WDN models used in this study were only verified using a 5-day water balance. The process involved a comparison of the daily change in tank water level of the case study area. This is considered as a limitation as the actual flows and pressures were not recorded in the study. This requires the use of high precision pressure sensors and data loggers for accurate calibration of the model. For distribution systems like the case study which are sensitive to pressure changes, measurement and pressure logging at critical nodes across the network was beyond the scope of the study due to time and financial constraints. However, this was not seen as a major problem with regards to obtaining meaningful results, because the hydraulic modelling approach and criteria used in the study are used in the same way in practice during design and operation test for new and existing water distribution systems.

The use of PDD analysis for intermittent water supply is limited to systems where pressure does not usually fall below a certain threshold. As such simulation results from the PDD analysis were considered to provide more insight into the effect IWS and low-pressure systems for comparison between required and actual demand.

## 9.4 Applications of the research

Intermittent water supply is such a serious problem that the International Water Association (IWA) deemed it fit to constitute a specialist group solely focused on IWS. There is the need therefore, to further explore the complex nature of this kind of water supply. The research presented in this thesis makes substantial contribution to existing knowledge on IWS especially for off-grid distribution systems in sub-urban areas, and to a wider extent, on the water and sanitation sector.

Based on primary evidence, the study has identified household responses to IWS, highlighting the different coping mechanisms employed by households to ensure they have water to use when supply is switched off. Some of these strategies have been found to have negative impact on other users as well as on the performance of the distribution system. Where satellite towns and residential estates are being built, the findings can be useful in informing stakeholders of the risks and consequences of poor water delivery systems.

One significant finding in the research is the way consumption patterns in IWS systems significantly vary as compared to 24-hour systems. This has been shown to cause more reduction in system pressure, consequently reducing levels of service. The new demand pattern can be used by modellers from both industry as well as the academic sector, to better understand how networks perform under IWS in the quest to find lasting solutions to the problems caused by IWS. The findings can be applied to design robust networks that will be able to withstand varying conditions exerted upon them by the effects of intermittent supply. On the other hand, within existing residential settings similar to the case study, cost effective solutions like the raising tank elevation can be applied to reduce the occurrence of low or negative pressure and improve equity in supply.

Nigeria is currently in the process of introducing a Water Resource Bill which seeks to ensure right to safe and equitable water through regulations and policies (Okeola and Balogun, 2017). This research can be applied when considering service improvement options. Instead of always spending funds on improving infrastructure, investment policies should also focus on regulating water use and behavior change that can significantly reduce the habit of overconsumption. This in turn, as indicated in this study, will improve equity in supply.

## 9.5 Recommendations for further research

This research has revealed a number of important aspects on the concept of operating intermittent water supply, particularly for small water distribution systems being fed by through source tanks. This study however merits further investigation, particularly since it can be assumed to transpire elsewhere in Nigeria and other similar low-income countries.

These include:

- Further detailed data collection should be carried out at household level to acquire data on individual pumps for use in calibration of hydraulic models for testing.
- More extensive studies should be carried out in areas with gravity fed systems where tanks completely drain before refilling.
- Further research is needed to investigate mathematical solutions for PDD analysis of systems with low or no reference pressure.

- Explore the possibility of employing optimisation techniques to upgrade IWS systems with limited water sources.
- Further research is required to establish the effect of IWS on household sanitation practices, especially in low income countries.

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# Appendix A

## Survey Questionnaire for Household Survey

| S/No | | | | Code |
|---|---|---|---|---|
| 1 | How long have you lived here? | | | |
| | | | | |
| 2 | How many people live in this Household? | | | |
| | Children under 5 Months | | | |
| | Children under 5 Years | | | |
| | Children between 5 and 16 years | | | |
| | Adults | | | |
| | | | | |
| 3 | How many people come to work here each day? | | | |
| | Children between 5 and 16 years | | | |
| | Adults | | | |
| | | | | |
| 4 | Can you tell me your main source of water? (note to enumerator to ask to see the source if it's not the tap – just to confirm what it is) | | | |
| | Tap in house/Yard | | | 1 |
| | Protected well/Borehole in yard | | | 2 |
| | Shallow/Open well in yard | | | 3 |
| | Borehole outside yard | | | 4 |
| | Shallow/Open well outside yard | | | 5 |
| | Water vendor delivery to house | | | 6 |
| | Water vendor delivery outside house | | | 7 |
| | Standpipe outside yard | | | 8 |

| | | | | |
|---|---|---|---|---|
| | Other | | | 9 |
| | | | | |
| 5 | Can you tell me any other sources of water that you also use? | | | |
| | Tap in house/Yard | | | 1 |
| | Protected well/Borehole in yard | | | 2 |
| | Shallow/Open well in yard | | | 3 |
| | Borehole outside yard | | | 4 |
| | Shallow/Open well outside yard | | | 5 |
| | Water vendor delivery to house | | | 6 |
| | Water vendor delivery outside house | | | 7 |
| | Standpipe outside yard | | | 8 |
| | Other | | | 9 |
| | Not Applicable | | | 0 |
| | | | | |
| 6 | If you ever purchase water from a vendor how do you purchase that water? | | | |
| | Tanker | | | 1 |
| | Tub | | | 2 |
| | Jerry Can | | | 3 |
| | Bottle | | | 4 |
| | Sachet | | | 5 |
| | Other | | | 6 |
| | Do not purchase water | | | 0 |
| | | | | |
| 7 | How much water (in litres) from question 6 above do you buy? | | | |
| | Tanker | | | |
| | Tub | | | |
| | Jerry Can | | | |
| | Bottle | | | |
| | Sachet | | | |

| | | | | |
|---|---|---|---|---|
| | Other | | | |
| | Not Applicable/Do not purchase water | | | 0 (missingV) |
| | | | | |
| 8 | Now, thinking about the tap water, how frequently available is the supply? | | | |
| | Time of supply: | | | |
| | *Morning* | | | 1 |
| | *Evening* | | | 2 |
| | *Morning and Evening* | | | 3 |
| | *Not Certain* | | | 4 |
| | | | | |
| | Average hours of supply per day | | | |
| | Days of supply per week | | | |
| | Seasonal (Weeks/Months per year) | | | |
| | | | | |
| 9 | When supply is switched on do you store water in the household? (Yes/No). If yes go to question 10. If No go to question 16. | | | |
| | Yes | | | 1 |
| | No | | | 2 |
| | | | | |
| 10 | Do you store water in containers inside the house? (Yes/No). If No go to question 12. | | | |
| | Yes | | | 1 |
| | No | | | 2 |
| | | | | |
| 11 | May I please have a look at your containers? (Then fill in container enumeration form). | | | |
| | | | | |
| | | | | |
| 12 | Do you have outdoor storage tanks? If no go to question 15. | | | |
| | Yes | | | 1 |

| | | | | |
|---|---|---|---|---|
| | No | | | 2 |
| | | | | |
| 13 | If yes, may I have a look at the tank? (note to enumerator – please note what type of tank this is then estimate the volume – if possible, please also take a photograph) | | | |
| | Overhead/Roof top tank | | | Yes=1,No=2 |
| | Surface tank | | | Yes=1,No=2 |
| | Underground tank | | | Yes=1,No=2 |
| | | | | |
| 14 | When the supply is switched on what do you do with remaining stored water? (Tick all that applies) | | | |
| | Throw remaining water away and refill containers | | | Yes=1,No=2 |
| | Refill containers by adding to remaining stored water | | | Yes=1,No=2 |
| | Use remaining water till it's finished and then refilling containers | | | Yes=1,No=2 |
| | Use water from tap and leave excess in container for later use | | | Yes=1,No=2 |
| | Other | | | Yes=1,No=2 |
| | | | | |
| 15 | In addition to water that you store, what else do you do with water running when tap is operational? (Tick all that applies) | | | |
| | Consumption (e.g. cooking and drinking) | | | Yes=1,No=2 |
| | Hygiene (personal and domestic cleanliness) | | | Yes=1,No=2 |
| | Amenity (e.g. car washing, lawn watering) | | | Yes=1,No=2 |
| | Productive use (e.g. animal watering, construction and small scale horticulture | | | Yes=1,No=2 |
| | | | | |
| 16 | Do you have booster pumps? (Yes/No) If No go to question 19. | | | |
| | Yes | | | 1 |
| | No | | | 2 |
| | | | | |

| | | | | |
|---|---|---|---|---|
| 17 | Is the pump connected to the distribution mains? (YES/NO) | | | |
| | Yes | | | 1 |
| | No | | | 2 |
| | Not applicable | | | 0 |
| | | | | |
| 18 | What is the primary use of the booster pump? | | | |
| | Pump to tank or storage container | | | 1 |
| | Increase water pressure for normal use | | | 2 |
| | Pump from underground/surface tank to overhead | | | 3 |
| | Other | | | 4 |
| | Not Applicable | | | 0 |
| 19 | Now thinking about water supply, would you still store water if supply was continuous and reliably available? (YES/NO) | | | |
| | Yes | | | 1 |
| | No | | | 2 |
| | | | | |
| 20 | When supply stops what do you do with your taps? | | | |
| | Leave tap open to continue storing water when supply resumes | | | 1 |
| | Leave tap closed till supply resumes | | | 2 |
| | Other | | | 3 |
| | | | | |
| 21 | Now thinking about the tap water when it is running, how would you classify the following? | | | |
| | *Pressure:* | | | |
| | Very Good *(Very satisfied)* | | | 4 |
| | Good *(Satisfied)* | | | 3 |
| | Poor *(Dissatisfied)* | | | 2 |
| | Very Poor *(Very dissatisfied)* | | | 1 |
| | *Colour:* | | | |
| | Very Good *(Very satisfied)* | | | 4 |

| | | | | |
|---|---|---|---|---|
| | Good *(Satisfied)* | | | 3 |
| | Poor *(Dissatisfied)* | | | 2 |
| | Very Poor *(Very dissatisfied)* | | | 1 |
| | *Taste:* | | | |
| | Very Good *(Very satisfied)* | | | 4 |
| | Good *(Satisfied)* | | | 3 |
| | Poor *(Dissatisfied)* | | | 2 |
| | Very Poor *(Very dissatisfied)* | | | 1 |
| | *Time and duration of supply:* | | | |
| | Very Satisfied | | | 4 |
| | Satisfied | | | 3 |
| | Dissatisfied | | | 2 |
| | Very Dissatisfied | | | 1 |
| | *Overall Supply:* | | | |
| | Very Satisfied | | | 4 |
| | Satisfied | | | 3 |
| | Dissatisfied | | | 2 |
| | Very Dissatisfied | | | 1 |
| | | | | |
| 22 | In comparison with the type of supply you receive, which of the following options would you prefer? | | | |
| | Continuous supply but with low pressure | | | 1 |
| | Intermittent Supply but with higher pressure | | | 2 |
| | | | | |

**Container Enumeration Form**

Name of Enumerator…………………………………Questionnaire No………………..

Household Code……………………………Date…………………….

| Container | Type | Number | Primary Use | Volume in litres | Total Volume in litres |
|---|---|---|---|---|---|
| | | | | | |
| | | | | | |
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