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HYDRAULIC SIMULATION OF LOW SKELETONISATION, LARGE-SCALE URBAN WATER DISTRIBUTION NETWORKS:
A CASE OF NAGURU WATER SUPPLY AREA, KAMPALA

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Hydraulic Simulation of Low Skeletonisation, Large-Scale Urban Water Distribution Networks:

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Master of Science Dissertation
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Declaration: The findings, interpretations and conclusions expressed in this study are the responsibility of the author. Whilst several authors have been consulted in this study, the ideas and findings of the study are original to the author.

For Daddy (RIP) and Mummy,
My siblings; Remi, Akampa, Msaud, Dembe, Edith, Kyatona, Esther,
the UCF family, the Buregyeya family, the Kaweera family and the Ssenkatuuka family.

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Mugisha Feriha Mukuve, 2010

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ABSTRACT

Hydraulic simulation (HS) offers functionality that could greatly enhance the resolution of the recurring technical challenges experienced by the Kampala Water distribution Network (KWN). Unfortunately, HS technology is in its infancy in the developing world and Uganda in particular, and thus no large-scale implementation of the technology exists to validate its applicability in the local context.

This research therefore sought to implement the internationally recommended hydraulic modelling (HM) guidelines and subject them to prevailing local conditions in the Kampala water distribution network (using the Naguru area network as the prototype), in order to evaluate their suitability. The process necessitated the construction of a large-scale, low-skeletonisation hydraulic model of a selected representative study network; calibrating the model; and performing several post-calibration accuracy assessment tests.

The construction process involved CAD to DXF drawing conversions, meter-aggregation and flow-distribution demand allocation, database-to-model synchronisation and preliminary model performance evaluation. Calibration and post-calibration field tests generated several datasets of network hydraulic parameters that were necessary for the analysis of the model's accuracy and consistency.

The inferences indicated first; that large-scale hydraulic simulation can be feasibly effected for the KWN using the internationally proposed guidelines, although, the calibrated hydraulic models are not automatically immune to extraneous discrepancies. In addition, the achieved accuracy levels are variable across the network, exceeding 50% variation in some locations.

Secondly, out of over 120 test locations, only 3 cases of gross discrepancy were observed, yet the internationally proposed calibration limits were fulfilled by only 1 of the 6 test datasets. This revealed that the existing international calibration-accuracy guidelines are mostly suitable for high-accuracy simulation and may erroneously discard valid simulation data when the objective lies within moderate accuracy, which is common for utilities in the developing world.

In general, the research findings derived from this study ultimately provide a yard-stick and platform for the subsequent application of the technology throughout the KWN service area and Uganda in general.

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Keywords:
Hydraulic Modelling, Water Distribution Networks, Genetic Algorithms, Network Calibration

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LIST OF ACRONYMS

A/Cs	Customer Accounts
Approx.	Approximate
AWWA	American Water Works Association
CAD	Computer-Aided Design
DEM	Digital Elevation Model
DXF	Drawing Exchange Format
EPA	Environmental Protection Agency
EPANET	Hydraulic Modelling Software developed by the USEPA
EPS	Extended Period Simulation
ESRI	Environmental Systems Research Institute
GA	Genetic Algorithm
GIS	Geographic Information System
GPS	Global Position System
GUI	Graphical User Interface
HS	Hydraulic Simulation
IWA	International Water Association
km^2	Square kilometres
KWN	Kampala Water distribution Network
KW	Kampala Water, Kampala, Uganda (A subsidiary of NWSC in charge of Kampala City)
l/s	Litres per Second - Units of Demand
NIS	Network Information Systems Department, Kampala Water
No.	Number
NRW	Non-revenue water
NWSC	National Water and Sewerage Corporation
PCV	Permanently Closed Valve
SCADA	Supervisory Control and Data Acquisition
UBOS	Uganda Bureau of Statistics
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey

WaterCAD	Water distribution modelling software developed by Haestad Methods
WDS	Water Distribution System
WSSM	Water Supply Simulation Model

CHAPTER ONE

1.0 INTRODUCTION

This chapter provides a background to the research and highlights the justification for undertaking the project. It includes a statement of the problem and delineates the scope of the research. Also covered herein are the objectives or goals of the research project.

1.1 GENERAL

Kampala Water (KW) under the National Water and Sewerage Corporation (NWSC) is currently charged with the supply of clean potable water to Kampala City, the Capital City of Uganda. The City's population is growing at a fast rate – 1.3 million people growing at 3.7% per annum (UBOS, 2005). As a consequence, the City's water distribution network is rapidly increasing in complexity and geographical extent. The increasing network complexity has been largely due to inadequate information on the network hydraulics and incomprehensive design methods; as well as lack of standard, systematic pipe laying practices resulting in significant 'spaghetti' networks (NWSC–KW, 2007). In addition, the technical performance of various sections of the water distribution network has been – and still is – in question with rampant 'dry-zone' (no-water) areas, recurrent water rationing, and unacceptably high levels of lost or non-revenue water (NWSC–KW, 2007).

Technical personnel at KW therefore urgently require comprehensive and reliable hydraulic network information with which to make sound decisions regarding the maintenance and expansion of the water network. Methodologies currently employed to operate and manage the network are based on engineering intuition, experience and rule-of-thumb techniques which are no longer sustainable with the existing complexity and growing extent of the network (KW GIS Section, 2004).

Simulation of the behaviour of a water distribution network using computer aided modelling is one of the most feasible ways of gaining an accurate engineering perspective of the network. The science of network hydraulic modelling, as developed over the years, is founded on the basic principles of mathematical hydraulics. With the aid of advanced computer technology, the hither-to untenable, complex and rigorous computations required for network simulation can now be feasibly executed. Hydraulic engineers throughout the world now have the opportunity to obtain fairly accurate representation of a physical water network's hydraulic parameters at a relatively reasonable expense.

In the developed world, guidelines have been proposed with procedures, assumptions and data collection methodologies for the effective construction and calibration of water distribution network models. Unfortunately, these guidelines are not certified as international modelling standards (Walski *et al.*, 2003, Savic *et al.*, 2009) and therefore cannot inspire confident application and utilisation of the technology in the local context. The reason for this is that although many of these model-construction and calibration assumptions, procedures and data collection techniques are often credibly scientifically validated, they have not been tested sufficiently using data obtained in real conditions (USEPA, 2005, Savic *et al.*, 2009).

Moreover, the testing of these guidelines has been carried out on well designed, well structured, fully charged pipe networks (full bore flow), characteristic of laboratory test networks and distribution systems in the developed world. These conditions differ significantly from the local context in Kampala. The Kampala network is characterised by 'spaghetti' connections, cases of partially-full flow in pipes, and under-designed network extensions (NWSC–KW, 2007). The reliability of modelling technology is therefore invariably largely subject to these attendant local conditions (Walski *et al.*, 2003).

For instance, internationally suggested model calibration guidelines recommend random sampling of water network features as test locations, and the use of genetic-algorithm optimisation techniques to adjust the model to accurately depict the physical network. The accuracy of the rest of the element parameters in the network is subsequently assumed to be satisfactory (AWWA, 2004). However, the validity of these techniques may vary given different water distribution networks. Their applicability therefore needs to be tested in the local context, before the technology can be confidently utilised for a utility's network operation and management (Ozdemir and Ucaner, 2007).

Establishing the technical-utility of hydraulic simulation technology and the practical-applicability of the proposed guidelines – given prevailing local conditions – is best achieved by large-scale application on actual water distribution networks. In the Ugandan context, prior to this study no large-scale low-skeletonisation models had ever been constructed. Consequently, the adoption and utilisation of the technology for large, complex water networks could not be done confidently because of the absence of practical benchmarks with which to evaluate the applicability of the technology.

On that note, decision support tools such as hydraulic simulations require validation in Uganda – and Kampala City in particular – in order to assess their efficacy and applicability, given the existing local conditions (Kizito *et al.*, 2007). Such a process generates a benchmark for the proliferation of the technology in those localities, and contributes to the ultimate development of international standards, which – in the case of hydraulic modelling – do not exist at the moment (Walski *et al.*, 2003). The result not only provides a platform for the development of solutions to the needs of the local utility but also enables the identification of areas of the science that require enhancement (Kizito, 2008).

This dissertation outlines a research project that has attempted to lay the foundation for the full-scale use of hydraulic modelling technology in Uganda. The research conclusions shed light on the applicability of the technology in this developing country, by evaluating techniques and procedures – derived from internationally suggested best-practices – that yield the desired functionality in the conditions offered by Uganda's developing economy.

This study required the examination of the nature and accuracy of a model developed using these guidelines; and the consistency in accuracy that was achieved at various locations of the post-calibration water network model. The process required the adoption of international best-practices and standards in the construction and calibration of the network hydraulic model, and a comparative analysis of the post-calibration accuracy of the network model. The findings from the analysis provided an indicator of the suitability of the technology and guidelines given the local context, and are a yardstick for the propagation of the technology in developing countries particularly Uganda.

1.2 RESEARCH QUESTIONS/HYPOTHESIS

Question 1: Do the proposed international model construction assumptions, best-practices, and data collection methodologies result in accurate calibration models; given the unique local conditions of the Kampala water distribution network, namely; poorly structured network configurations, inadequate flows resulting in partially full pipe-flows, improperly designed network extensions?

Question 2: More specifically, are models calibrated using the Genetic Algorithm optimisation technique accurate and is this accuracy consistent throughout the simulated network?

Question 3: Lastly, are the internationally proposed calibration guidelines (produced by AWWA, 1999) suitable for models calibrated for the local context?

The research hypothesis was that all these questions have affirmative (yes) answers. The study was therefore undertaken to test this hypothesis according to the corresponding research objectives. The research conceptual framework in Figure 1 illustrates research context and goals in pictorial detail.

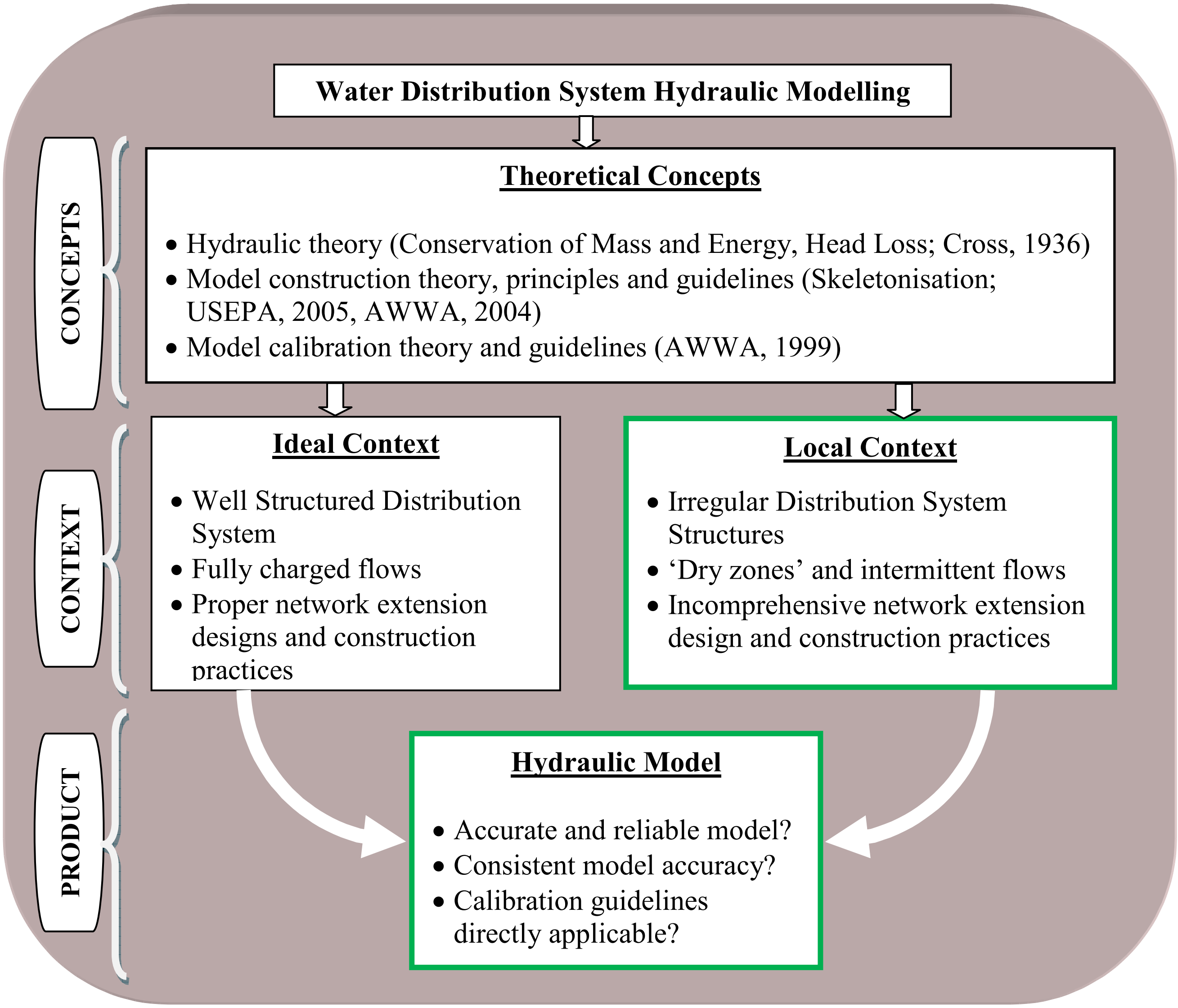

Figure 1: *Research Conceptual Framework detailing the study context, questions, and goals*

Given the above described study questions, the research problem statement was formulated as indicated in the subsequent section.

1.3 STATEMENT OF THE PROBLEM

Due to the various challenges of an increasingly complex and expanding water distribution network, the Kampala water utility urgently required hydraulic modelling functionality as a source of reliable intelligence concerning the hydraulic behaviour of the system. Unfortunately, hydraulic simulation technology is in its infancy in the developing world and Uganda in particular. Therefore prior to this study, no large-scale implementation of the technology (large-scale low-skeletonised operational models) existed in Uganda with which to validate its applicability in the local context.

Moreover, internationally suggested hydraulic model construction and calibration assumptions, best-practices, and data collection methodologies have not been globally standardised, and therefore require practical validation prior to their adoption for a given locality. For instance, model calibration guidelines recommend random sampling of water network features as test locations, and the use of genetic-algorithm optimisation techniques to adjust the model to accurately depict the physical network. The accuracy of the rest of the element parameters in the network is subsequently assumed to be satisfactory. The validity and suitability of these assumptions and guidelines had not been established for the prevailing Kampala City network conditions, which posed serious limitations to the applicability of the technology in addressing the City water utility's challenges. These concerns called for practical validation of the technology in the local context, hence the theme of this study.

1.4 SCOPE

The entire KWN requires hydraulic modelling. However, for purposes of this research only the Naguru water supply area was studied. The Naguru water supply network was deemed as sufficiently representative of the Kampala water network because of its comparatively extensive geographic coverage, approximately distinct coverage area (where mains circulating in a given area carry water from one major source), and significant number of customer connections (see Figure 2, Table 1). This selection was also limited by the available resources and time. It should be noted that the demarcation of the Naguru area network was not based on Kampala Water utility company's administrative branch systems but rather on the source reservoir from which water is distributed as shown in Figure 2.

The research made use of one of the leading commercially available software packages, namely; WaterCAD by Haestad Methods. This package was selected because of its ready availability, ease of use, and its incorporation of the latest advancements in the field of hydraulic modelling as highlighted herein. In addition, while water network modelling covers both the hydraulics and water quality characteristics of the system, the scope of this study was limited to the hydraulic parameters of the distribution network model.

Table 1: *Comparison of water sources' coverage in the Kampala water network*
(Source: KW GIS Office, 2008)

Administrative Branch	**No. of A/Cs in Branch**	**Main Hydraulic Source**	**Approx. Total A/Cs per Source**	**Approx. Total Coverage Area (km^2)**	**Connection Intensity (A/Cs/km^2)**
Kitintale	*9831*	Mutungo Tanks	9831	54.55	180.22
Kansanga	*15552*	Muyenga Reservoirs*	43886	324.62	135.19
Najjanankumbi	*14296*	-ditto-			
Mukono	*3181*	-ditto-			
Nakulabye	*10857*	-ditto-			
Ntinda	*15631*	Naguru Reservoir	26392	75.25	350.72
Kireka	*10761*	-ditto-			
City Centre	*10031*	Nakasero Reservoir*	24635	138.53	177.83
Bwaise	*14604*	-ditto-			
Nateete	*11100*	Rubaga Reservoir	16555	72.90	227.09
Nansana	*5455*	-ditto-			
Total	**121,299**				

* Muyenga and Nakasero are primary sources in the network and thus possess highly complex coverage areas (see Figure 2). They were therefore deemed unsuitable for this analysis

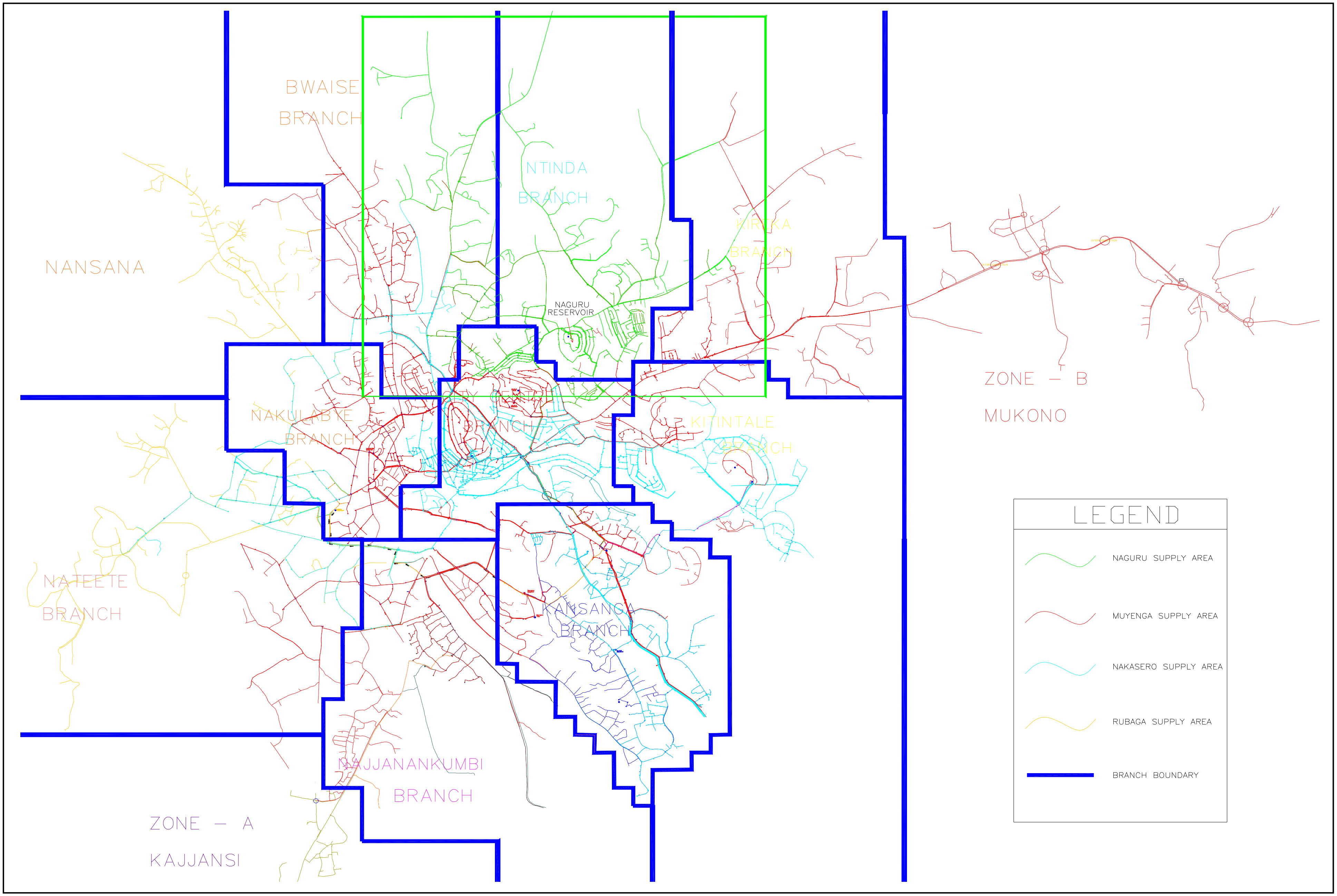

Figure 2: *Naguru Supply Area relative to the Kampala Water Network and Administrative Units. (Source: KW GIS Office, 2008)*

1.5 OBJECTIVES

This section details the main and specific objectives of the research.

1.5.1 MAIN OBJECTIVE

The major goal of this research was to construct and assess the reliability of a large-scale hydraulic model calibrated using internationally suggested modelling assumptions, best-practices, and data collection methodologies, given the prevailing local conditions of the Kampala water distribution network.

1.5.2 SPECIFIC OBJECTIVES

- To identify the hydraulic simulation needs of the Kampala Water Utility Company in reference to the Naguru water supply area as an adequate representation of the City's entire network.

- To construct an extended-period-simulation (EPS) hydraulic model of the study area using a selected software package. This involved assembling and defining the geo-spatial and hydraulic attributes of the elements of the Naguru water supply network.

- To calibrate the model to acceptable levels using internationally proposed model calibration best-practices based on genetic-algorithm optimisation and random selection techniques.

- To assess the model's reliability, and hence the validity of the utilised model construction and calibration guidelines subject to prevailing local conditions by assessing the consistency of the attained levels of accuracy in the post-calibration model network. This required several *post-calibration validation* tests, and a comparative analysis between accuracy levels attained at calibration and those recorded from the post-calibration experimental surveys.

1.6 RESEARCH OUTPUTS

The outcome of this research was a model that simulates and effectively communicates the hydraulic transformations in Naguru water supply area. The adopted methodologies and analysis provided a tangible indication of the reliability of the internationally suggested guidelines, given prevailing local conditions. The study thereby generated tentative standards for subsequent propagation of hydraulic modelling technology throughout the country.

CHAPTER TWO

2.0 REVIEW OF LITERATURE

This chapter seeks to provide an evaluation of previous work done on hydraulic modelling and its application to urban water distribution networks. Also provided herein are details of the available hydraulic modelling technologies and software, their relevance, and details of their applicability in the Ugandan situation. The chapter also gives the definitions for key terms adopted in the study.

2.1 DEFINITIONS

The following definitions were adopted for this research:

Network Modelling is the process of building, verifying and operating network models of distribution systems, which provide valuable insights into operational practices (Halcrow, 2002).

Model calibration is the process of comparing the model results to field observations and, if necessary, adjusting the data describing the system until model-predicted performance reasonably agrees with measured system performance over a wide range of operating conditions (Walski *et al.*, 2003)

2.2 HISTORY OF HYDRAULIC MODELLING

The science on which water network hydraulic analysis is based was first suggested by Hardy Cross using an iterative method (Cross, 1936). It is what was used throughout the water industry for about forty years (USEPA, 2005). The advent of computer-based hydraulic simulation leveraged the power of the computer to solve Hardy's complex equations and permutations required to adequately simulate a water distribution network. By 1980s, these superior computer-based techniques had witnessed significant proliferation (Wood, cited in USEPA, 2005).

Practical application of hydraulic modelling progressed significantly in the 1990s with the introduction of the public domain EPANET model (Rossman, 2000) and other Windows-based commercial water distribution system models.

Early simulation packages simulated the hydraulic parameters of a water network under steady-state conditions (constant demand and network operations). However, advances in applications development now allow for the construction of models that reflect both the temporal and spatial behaviour of the network, known as Extended Period Simulation (EPS) models. Hydraulic modelling functionality has therefore become essential in the global water industry and is now an integral part of most water system design, master planning, and fire flow analyses, particularly in the developed world (Walski *et al.*, 2003).

Figure 3 illustrates the evolution of hydraulic and water quality models since the 1930s.

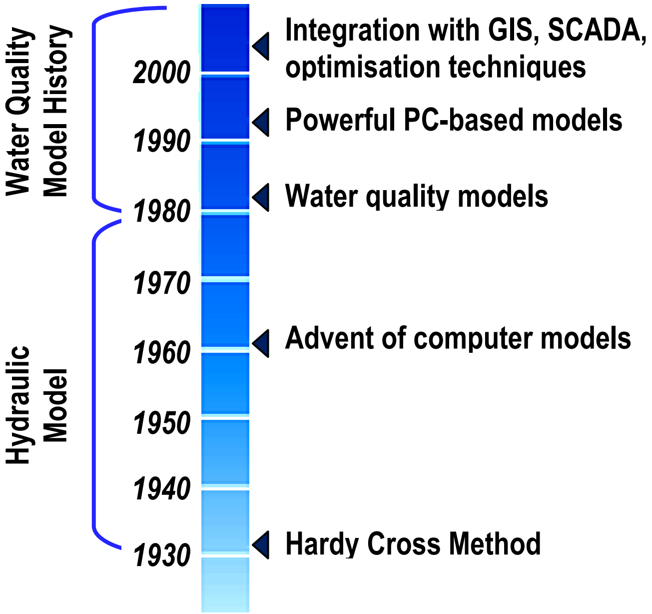

Figure 3*: Illustration of the Evolution of Hydraulic and Water Quality Models (USEPA, 2005).*

2.3 OVERVIEW OF THEORETICAL CONCEPTS

Hydraulic modelling theory and application is adequately detailed in several references (Walski *et al.*, 2003; USEPA, 2005, AWWA, 2004). A synopsis of this information adopted from these references is given here below:

The three fundamental principles used to compute fluid flow in a pipe network are;

- **Conservation of Mass:** This principle requires that the sum of the mass flows in all pipes entering a junction must equal the sum of all mass flows leaving the junction. Because water is essentially incompressible, conservation of mass is equivalent to conservation of volume.

- **Conservation of Energy:** There are three types of energy in a hydraulic system: kinetic energy associated with the movement of the fluid, potential energy associated with the elevation, and pressure energy. In water distribution networks, energy is referred to as "head" and energy losses (or head-losses) within a network are associated primarily with friction along pipe walls and turbulence.

- **Pipe Friction Head-loss:** Flow through pipe networks is significantly affected by the friction head-loss. Three empirical equations usually used are the Darcy-Weisbach, the Hazen-Williams, and the Manning equations. All three equations relate head or friction loss in pipes to the velocity, length of pipe, pipe diameter, and pipe roughness. An essential relationship that is important for hydraulic analysis is the Reynolds number, which is a function of the kinematic viscosity of water (resistance to flow), velocity, and pipe diameter. The most widely used head-loss equation in the U.S. is the Hazen-Williams equation (Walski *et al.*, 2003). Though the Darcy Weisbach equation is generally considered to be theoretically more rigorous, the differences between the use of these two equations is typically insignificant under most circumstances (USEPA, 2005).

Water distribution models represent these basic principles (conservation of mass and conservation of energy) as a series of linear and non-linear equations. The non-linearity of these equations requires that iterative solution methods be used to numerically solve the set of equations. The most common numerical method utilised is the Newton-Raphson method (USEPA, 2005).

A distribution system is represented in a hydraulic model as a series of links and nodes. Links represent pipes whereas nodes represent junctions, sources, tanks, and reservoirs (see Figure 4). Valves and pumps are represented as either nodes or links depending on the specific software package.

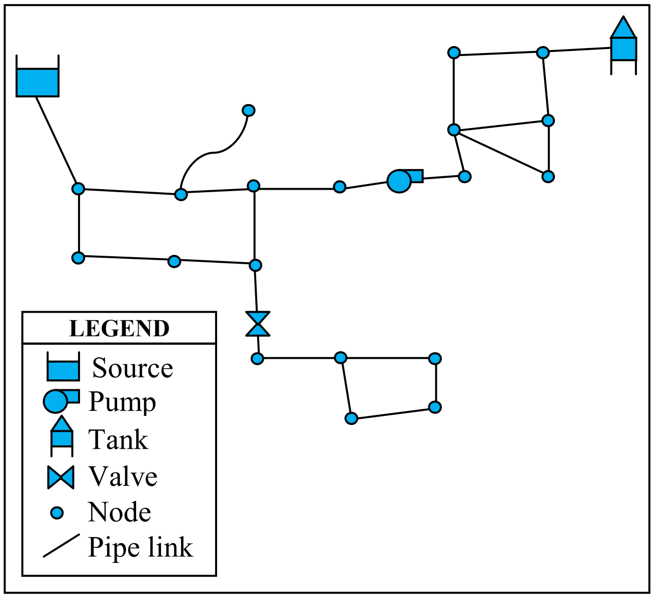

***Figure 4**: Simple Link-Node Representation of a Water Distribution System (USEPA, 2005).*

Drinking water distribution systems, as noted earlier, can be analysed either in steady-state or EPS. For purposes of this study, an EPS model was constructed. In a steady-state analysis, all demands and operations are treated as constant over time and a single solution is generated. In the EPS mode, variations in demand, tank water levels, and other operational conditions are simulated by a series of steady-state analyses that are linked together. Each steady-state solution in the EPS mode involves a separate solution of the set of non-linear equations. Though the EPS solution does introduce some approximations and ignores the transient phenomena resulting from sudden changes (e.g., a pump being turned on), these more refined assumptions are generally not considered significant.

The *fundamental equations* for hydraulic analysis are as follows:

Conservation of Mass: In EPS, if storage is involved, a term for describing the accumulation of water at those nodes is included. Mathematically, the principle can be represented as follows:

$$\Sigma Q_{\text{in}} - \Sigma Q_{\text{out}} = q_{\text{ext}}$$ *(Equation 2.1: Lansey and Mays, 2000)*

Where Q_{in} = Total flow into the node, Q_{out} = Total demand at the node, q_{ext} is the external demand or supply.

Conservation of Energy: The conservation of energy principle requires that the difference in energy between two points in a network must be the same regardless of flow path. For hydraulic analysis, this principle can be represented in terms of head as follows:

$$Z_1 + \frac{P_1}{\gamma} + \frac{V_1^2}{2g} + \sum h_P = Z_2 + \frac{P_2}{\gamma} + \frac{V_2^2}{2g} + \sum h_L + \sum h_M$$ *(Equation 2.2: USEPA, 2005)*

where: $Z_{1 \text{ and } 2}$ = elevation at points 1 and 2, respectively, in ft (m), $P_{1 \text{ and } 2}$ = pressure at points 1 and 2, respectively, in lb/ft^2 (N/m^2), γ= fluid (water) specific weight, in lb/ft^3 (N/m^3), $V_{1 \text{ and } 2}$ = velocity at points 1 and 2, in ft/s (m/s), g = gravity acceleration, in ft/sec^2 (m/sec^2), h_P = pumping head gain, in ft (m), h_L = head loss in pipes, in ft (m), h_M = loss due to minor losses, in ft (m).

Pipe-friction head-loss: The equation most commonly used in modelling software for computation of pipe-friction head-loss is the Hazen-Williams equation represented as follows:

$$\Delta P = 10.67 \text{ x } \left(\frac{Q}{C}\right)^{1.85} \frac{1}{D^{4.87}}$$ *(Equation 2.3: Walski et al., 2003)*

where ΔP = frictional pressure drop in m of water per m of pipeline, Q = flow rate (m^3/s), D = pipe inside diameter (mm), C = Hazen-Williams C factor (dimensionless)

2.4 BASIC HYDRAULIC MODEL INPUT CHARACTERIZATION

Building a network model, particularly if a large number of pipes are involved, is a complex process. The following categories of information are needed to construct a hydraulic model:

- Characteristics of the pipe network components (pipes, pumps, tanks, valves).
- Water use (demands) assigned to nodes (temporal variations required in EPS).
- Topographic information (elevations assigned to nodes).
- Control information describing how the system is operated (e.g., mode of pump operation).
- Solution parameters (e.g., time steps, tolerances as required by the solution techniques).

Commonly used methods for these parameters are briefly described in the following subsections.

2.4.1 PIPE NETWORK PARAMETERS

Construction of the pipe network and its characteristics may be done manually or through use of existing spatial databases stored in GIS or CAD packages. The initial step in constructing a network model is to identify pipes to be included in the model. Nodes are usually placed at pipe junctions, or at major facilities (tanks, pumps, control valves), or where pipe characteristics change in diameter, "C" value (roughness), or material of construction. Nodes may also be placed at locations of known pressure or at sampling locations or at locations where water is used (demand nodes). The required pipe network component information includes the following:

- pipes (length, diameter, roughness factor),
- pumps (pump curve),
- valves (settings), and
- tanks (cross section information, minimum and maximum water levels).

Skeletonisation is the process of selecting for inclusion in the model only the parts of the hydraulic network that have a significant impact on the behaviour of the system (Walski *et al.*, 2003).

Different modelling outlooks present differing views concerning skeletonisation. One extreme vouches for maximum skeletonisation of hydraulic models to avoid the voluminous quantities of information generated from a larger model. The other seeks to achieve maximum representation of the water network by including all network features to avoid omission errors.

Though there is no international standard for skeletonisation. The U.S. Environmental Protection Agency (EPA) draft guidance issued for modelling suggests inclusion of (USEPA, 2003, cited in USEPA, 2005):

- At least 50 percent of total pipe length in the distribution system.
- At least 75 percent of the pipe volume in the distribution system.
- All 12-inch diameter and larger pipes.
- All 8-inch and larger pipes that connect pressure zones, influence zones from different sources, or are known or expected to be significant conveyors of water.
- All 6-inch and larger pipes that connect remote areas to the main portion of the system.
- All storage facilities with controls or settings applied to govern the open/closed status of the facility that reflect standard operations.
- All active pump stations with realistic controls or settings applied to govern their on/off status that reflects standard operations.
- All active control valves or other system features that could significantly affect the flow of water through the distribution system.

In practice the level of skeletonisation is governed by the ultimate purpose of the simulation, with models for master planning or regional water studies, requiring a broader level of skeletonisation while those for detailed design work or water quality studies, require near accurate representations of the real-world system (Walski *et al.*, 2003).

The model constructed for this research was skewed to the latter perspective (low skeletonisation); including a considerable level of the network detail. Skeletonisation was limited to mains with nominal diameters greater or equal to *50mm* representing nearly complete data capture of all updated transmission and distribution mains and fixtures, as indicated in the KW GIS maps of the study area.

It is important to note here that while *low skeletonisation* results in models including most of network features (high complexity), it does not necessarily ensure a large geographical extent to the model, which was considered important for this study. Thus the model constructed for this research was both ‘low skeletonisation’ and ‘large-scale’ emphasising its coverage of a large geographical area. The significance of a large geographical area was to ensure that the modelled pipe flows and pressures could be evaluated over large distances (distances greater than three kilometres).

2.4.2 WATER DEMAND PARAMETERS

Water consumption or water demand is the driving force behind the operation of a water distribution system. Any location at which water leaves the system can be characterized as a demand on the system. The water demands are aggregated and assigned to nodes, which represents an obvious simplification of real-world situations in which individual house taps are distributed along a pipe rather than at junction nodes. It is important to be able to determine the amount of water being used, where it is being used, and how this usage varies with time (Walski *et al.*, 2003).

Demand may be estimated by a count of structures of different types using a representative consumption per structure, meter readings and the assignment of each meter to a node (billing records), and to general land use. A universal adjustment factor should be used to account for losses and other unaccounted water usage so that total usage in the model corresponds to total production.

If meters are employed throughout a system, they can be the best source of data for determining demands (Walski *et al.*, 2003). Customers are typically billed based on a volumetric measure of usage, with meter readings taken on a monthly or quarterly cycle. Using these periodically recorded usage volumes, customers' average usage rates can be computed.

2.4.2.1 Using GIS for Demand Allocation

An integral part of creating a water distribution model is the accurate allocation of demands to the node elements within the model (Walski *et al.*, 2003). The spatial analysis capabilities of GIS make it a logical tool for the automation of the demand allocation process. The three main strategies of using GIS for demand allocation are; *Meter Assignment, Meter Aggregation and Flow Distribution*. These are discussed here below.

Meter Assignment

This allocation strategy uses the spatial analysis capabilities of GIS to assign geocoded (possessing coordinate data based on physical location, such as an x-y coordinate) customer meters to the nearest demand node. Therefore, this type of model loading is a point-to-point demand allocation technique, meaning that known point demands (customer meters) are assigned to network demand points (demand nodes). Meter assignment is the simplest technique in terms of required data, because there is no need for service polygons to be applied (see Figure 5).

However, meter assignment can prove less accurate than the more complex allocation strategies because “nearest” is determined by straight-line proximity between the demand node and the consumption meter. Piping routes are not considered, so the nearest demand node may not be the location from which the meter actually receives its flow.

In addition, the actual location of the service meter may not be known. Ideally, these meter points should be placed at the location of the tap, but the centroid of the building or land parcel may be all that is known about a customer account.

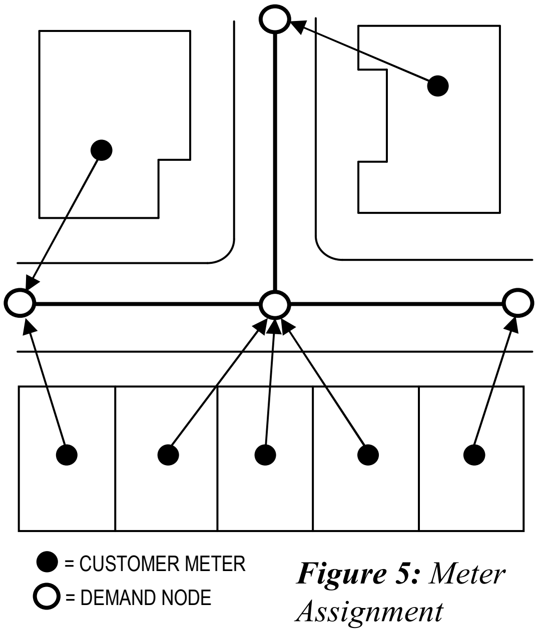

Figure 5: *Meter Assignment*

(Source: Walski et al., 2003)

Meter Aggregation

Meter aggregation is the technique of assigning all meters within a service polygon to a specified demand node (see Figure 6). Service polygons define the service area for each of the demand junctions.

Meter aggregation is a polygon-to-point allocation technique because the service areas are contained in a GIS polygon layer and the demand junctions are contained in a point layer. The demands associated with each of the service-area polygons are assigned to the respective demand node points.

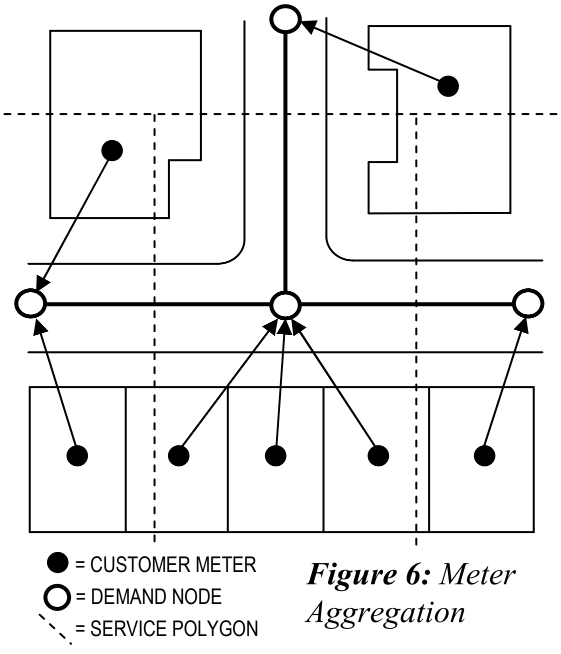

Figure 6: *Meter Aggregation*

(Source: Walski et al., 2003)

Because of the need for service polygons, the initial setup for this approach is more involved than for the simpler meter assignment strategy, with the trade-off being greater accuracy and control over the assignment of meters to demand nodes. Automated construction of the service polygons may not produce the desired results, so it may be necessary to manually adjust the polygon boundaries, especially at the edges of the drawing.

Flow Distribution

This strategy involves distributing a lump-sum demand among a number of service polygons (service areas) and, by extension, their associated demand nodes (Figure 7). The lump-sum area is a polygon for which the total (lump-sum) demand of all of the service areas (and their demand nodes) is known (metered), but the distribution of the total demand among the individual nodes is not. Lump-sum areas can be based on pressure zones, meter routes, or other criteria. Flow distribution strategies require the definition of lump-sum area or population polygons, service polygons, and their related demand nodes.

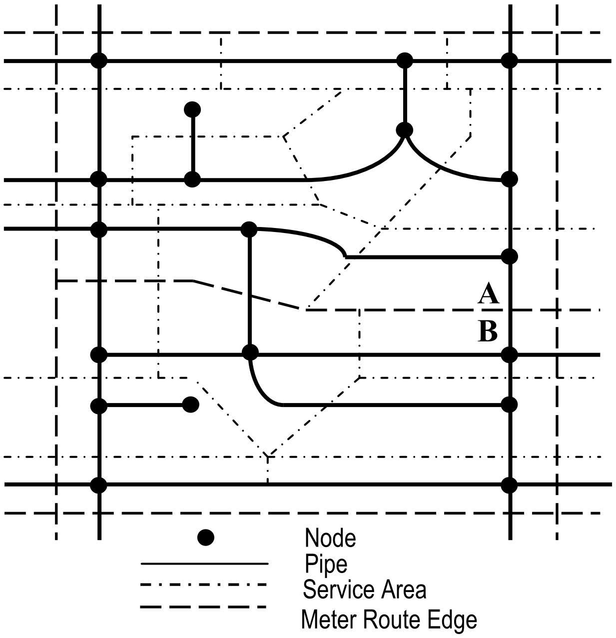

Figure 7: *Flow Distribution*
(Source: Walski et al., 2003)

Sometimes, a combination of demand allocation methods is recommended. One case where this technique is particularly helpful is in accounting for non-revenue water (NRW). NRW is the difference between the volume of water put into a system and the volume of water paid for by the customers and it comprises two components – Physical Losses and Apparent Losses (Halcrow, 2002).

A meter assignment or meter aggregation method can be used to distribute the normal demands, and a flow distribution technique can be used in addition to assign the NRW. In this study, *meter aggregation* demand allocation method (based on demand polygons) was adopted, to provide maximum accuracy and control; while *flow distribution* was adopted for the assignment of NRW.

2.4.2.2 Temporal Variations in Water Usage

In order to use a model in the EPS mode, information on temporal variations in water usage over the period being modelled is required. Spatially different temporal patterns can be applied to the individual network nodes. The best available information should be used for developing temporal patterns in order to make EPS most effective. For example, some users may have continuous water metering data, while others may use literature values as a first approximation for estimating residential temporal patterns. Temporal patterns also vary with climate. For example, lawn watering in summer months causes a spike in usage of water during that time period. In some cases, information from SCADA systems can be used to estimate system-wide temporal patterns.

A typical hierarchy for assigning demands includes the following:

- **Baseline Demands**: Baseline demands usually correspond to consumer demands and unaccounted-for-water associated with average day conditions. This information is often acquired from a water utility's existing records, such as customer meter and billing records. Although the spatial assignment of these demands is extremely important and should include the assignment of customer classes such as industrial, residential, and commercial use, actual metering data should be used when available. The baseline prevailing situation was the focus of this study, and therefore the baseline demand was the sole scenario adopted for the study.

- **Seasonal Variation**: Water use typically varies over the course of the year with higher demands occurring in drier months. When developing a steady-state model, the baseline (average day) demand can be modified by multipliers in order to reflect other conditions such as maximum day demand, peak-hour demand, and minimum day demand.

- **Fire Demands**: Water provided for fire services can be the most important consideration in developing design standards for water systems. Typically, a system is modelled corresponding to maximum-use conditions, with needed fire-flow added to a single node at a time. It is not uncommon for a requirement that multiple hydrants be flowing simultaneously.

- **Diurnal Variation**: All water systems are unsteady due to continuously varying demands. It is important to account for these variations in order to achieve an adequate hydraulic model.

> Diurnal varying demand curves should be developed for each major consumer class or geographic zones within a service area. For example, diurnal demand curves might be developed for industrial establishments, commercial establishments, and residences. Large users such as manufacturing facilities may have unique usage patterns.

Future water use: For design and planning purposes, a water system must be examined under future conditions. In situations where a system is largely currently built out, future demands may be estimated by developing global or regional multipliers that are applied to current demands. However, in new or developing areas, existing water use does not provide a useful basis for estimating future demands. Alternative approaches use population-based projections, socioeconomic modelling, and land-use methods (Johnson and Loux, 2004, cited in USEPA, 2005).

In estimating future demands for use in a network model, the most appropriate method is generally the land-use method. The land-use method is based on mapping land uses and then applying a water-use factor to each land-use category. When applied to existing situations or in historical reconstruction of water systems, aerial photographs are most commonly used as the base map for identifying land-use categories. For development of future demands, land–use maps can be obtained from planners. The land-use methodology is depicted in Figure 8.

Land-use unit demands or water-use factors are typically developed in units of gallons per day (GPD) per acre from local historical consumption data or from available regional information. GIS technology is frequently used as a means of developing and manipulating the land-use polygons and assigning the calculated demands to the model nodes.

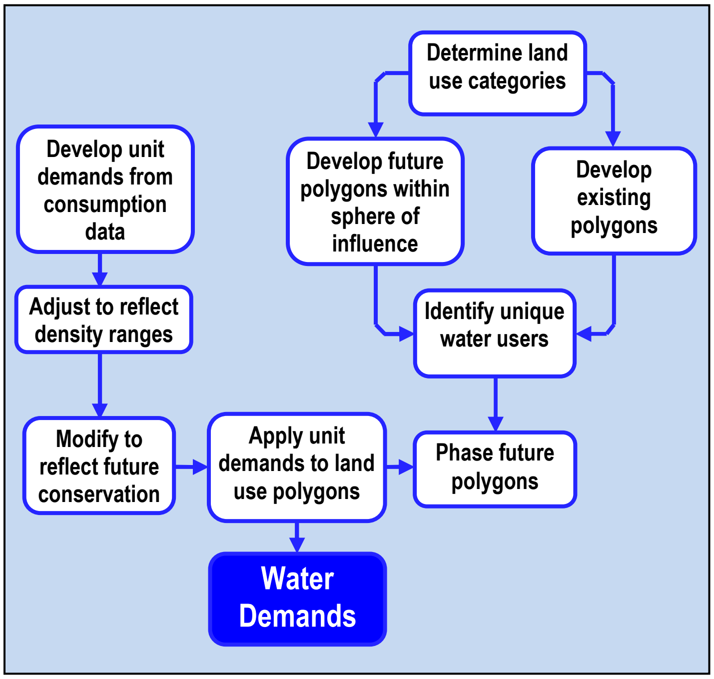

***Figure 8**: A Flow Chart for Estimating Future Water Demand Based on Land-Use Methodology (USEPA, 2005).*

2.4.3 TOPOGRAPHICAL PARAMETERS

Hydraulic models use elevation data to convert heads to pressure. Actual pipe elevations should be used to establish the correct hydraulic grade line. Elevations are assigned to each node in a network where pressure information is required. Various techniques are used to determine elevation information including the following:

- **Topographical maps:** Paper topographical maps produced by the United States Geological Survey (USGS) or other local agencies may be used to manually interpolate elevations for nodes. The relative accuracy depends upon the degree of topography in the area, the contour elevations on the map, and the manual takeoff methods used.
- **Digital elevation models (DEM):** USGS and other agencies produce digital files containing topographical information. When used with various software tools, elevation information can be directly interpolated and assigned to nodes based on the coordinates of the nodes. The accuracy of this process depends upon the degree of detail in the DEM.
- **Global Positioning Systems (GPS) or other field survey methods:** Standard field surveying techniques or modern surveying methods using a GPS satellite can be used to measure elevations at nodes. The modern GPS units can calculate elevation by using four or more satellites. However, elevation is the most difficult calculation for a GPS unit, and depending upon the location surveyed, it may be prone to significant error.

At the time of the research, no DEM with highly detailed accuracy was available for the country. The available DEM was found to be unsuitable as it had an 90-meter contour interval and was last updated in the 1980's. Topographical maps for country could only be obtained at unsuitable scales while GPS field survey equipment was not available.

For this research therefore, GIS map data for the model was obtained from the KW GIS office. The utility acquired these maps from the Uganda Department of Lands and Surveys located in Entebbe, which generated these maps from a relatively high accuracy aerial photograph survey done in the early 1990's. The interval of these maps was 10 meters densified to 2 meters.

2.4.4 MODEL CONTROL PARAMETERS

In order to apply an EPS model, it is necessary to define a set of rules that tells the model how the water system operates. This may be as simple as specifying that a particular pump operates from 7:00 AM to 10:00 AM each day. Alternatively, it may be a set of complex "logical controls" in which operations such as pump off/on, pump speed, or valve status are controlled using Boolean operators (including if-then-else logic) for factors such as tank water levels, node pressures, system demand, and time of day (Grayman and Rossman, 1994). For water systems that operate automatically based on a set of rules, determination of these rules are quite straightforward. For manual systems, the rules must be determined by interviews with system operators.

2.4.5 EXTENDED PERIOD SIMULATION (EPS) SOLUTION PARAMETERS

Solution techniques used to iteratively solve the set of non-linear equations typically have various global parameters that control the solution technique. These parameters may be time-step lengths for EPS runs or tolerance factors that tell the model when a solution is considered to have converged.

The user must specify the values for the solution parameters, or (as is frequently done) accept the default values that are built into the software products. The specific solution parameters vary between solution techniques and specific software products.

2.5 GENERAL CRITERIA FOR MODEL SELECTION AND APPLICATION

The initial step in modelling is to define the basic scope and needs of the modelling process and to select an appropriate software package that satisfies both the specific needs of the current project and likely future needs. Factors that may enter into the selection of a software package include:

- technical features,
- training/support and manuals,
- user interface,
- integration with other software (such as GIS, CAD),
- compatibility with EPANET,
- cost, and
- response from existing users.

A summary of major available hydraulic-water quality modelling software is provided in Section 2.6. Once a suitable model has been selected, the following steps should be followed in applying network models (Clark and Grayman, 1998):

- *Develop* the basic network model.
- *Calibrate* and validate the model.
- *Establish clear objectives* and apply the model in a manner to meet the objectives.
- *Analyze* and display the results.

2.5.1 DEVELOPING A BASIC NETWORK MODEL

The basic network model inputs should be first characterized using the techniques described in Section 2.4. The model should be developed based on accurate, up-to-date information. Information should be entered carefully and checked frequently. Following the entry of the data, an initial run of the model should be made to check for reasonableness. Figure 9 provides a conceptual framework of the network modelling process.

2.5.2 MODEL CALIBRATION AND VALIDATION

Calibration is an integral aspect of the art of modelling water distribution systems. Model calibration is “the process of adjusting model parameter data (or, in some cases, model structure) so that the simulated hydraulic and water quality output sufficiently mirrors observed field data” (Walski *et al.*, 2003). Depending on the degree of accuracy desired, calibration can be difficult, costly, and time-consuming. The extent and difficulty of calibration are minimized by developing an accurate set of basic parameters that provide a good representation of the real network and its components.

Discrepancies identified between the field data and model simulations are then eliminated by adjusting the model elements’ hydraulic parameters until an acceptable level of accuracy is attained. This process requires both *macro-calibration* (eliminating large discrepancies) and *micro-calibration* (fine-tuning the model’s accuracy).

2.5.2.1 Macro-calibration

This involves simply examining the general trends in the model and the simulated behaviour of the network based on previous experience and general logic, to identify large discrepancies between the model and the existing network. Incongruence identified at this level includes the existence of large zones of low pressure where they do not actually exist, unusual levels of water etc.

Some pointers during macro-calibration include:

- Pipes with flow velocities greater than 1.5m/sec
- Head losses greater than 1m per 100meters or 10m per kilometre
- Large diameter pipes with head losses greater than 3m per kilometre

2.5.2.2 Sensitivity Analysis

Next, a sensitivity analysis can be conducted to judge how performance of the calibration changes with respect to parameter adjustments (Walski *et al.*, 2003). This involves making global and local adjustments to the model parameters to observe the general effect this has on the simulated hydraulics. Sensitivity analysis is particularly relevant when large demand scenarios (such as fire flows) are considered in the model. Base-line scenarios will most likely have no significant impact on system heads (Walski *et al.*, 2003). For this study the sensitivity analysis was not carried out since the model was constructed for the Base-line demand scenario which would likely result in inconsequential sensitivity analysis results.

2.5.2.3 Micro-calibration

Involves synchronising the model's output to the existing conditions on the ground to an acceptable and representative level of accuracy. This is achieved in two steps starting with *preliminary testing* (of sample selected network locations). The second step is a fine-tuning process to minimise the discrepancy between model-generated hydraulics and the field-observed hydraulics. Typical model calibration therefore requires the collection of several sets of pressure and flow test data from the physical network, which can then be compared with model generated values.

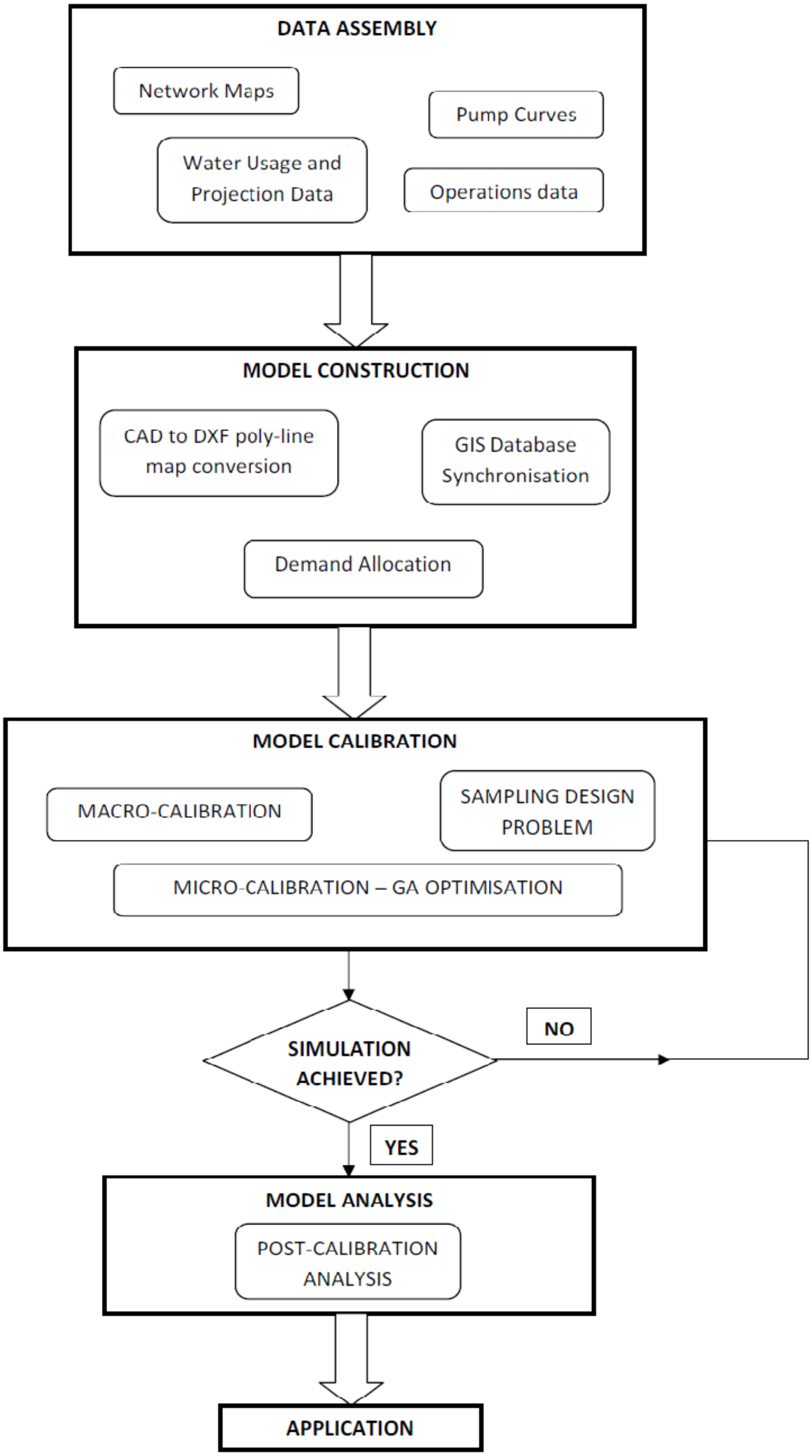

Figure 9: *NETWORK MODELLING PROCESS FLOW CHART*

After the micro-calibration fine-tuning, *post-calibration/validation testing* can be done to assess the sensitivity of the most accurate calibration combinations arrived at during the synchronisation process. This can be carried out by subjecting the model to measured parameters as observed from validation tests (such as fire flow tests) on the physical network and comparing the model's results with the field results. Although it is desirable to validate every model, most utilities do not have the time or money required to perform a thorough verification of the entire system (Walski *et al.*, 2003). Validation tests are therefore not often regarded as essential prerequisites for the use of the model. Given the constraints on this research, model validation testing was not carried out.

2.5.2.4 Micro-calibration pressure and flow testing – *preliminary testing*

This is carried out to examine the levels of accuracy between the model and the actual physical network. Field test locations for this exercise are identified through a process known as the *sampling design problem* which essentially defines the limiting calibration criteria that delineate the test-location sample space (Walski *et al.*, 2003). Test-location sampling is done randomly and the following limiting criteria often used (AWWA, 1999):

- Sampling points should be at the extremities of the network, a considerable distance from the Boundary nodes in the network (reservoirs and tanks).
- Selected points should also have relatively high discharges and pressures.

The actual values of the minimum distance from boundary nodes, minimum discharge, and minimum pressure are relative and unique to a given model. They are therefore selected having considered the system hydraulics and constraints of the modelling environment (Kapelan, 2003).

However, prior to testing reconnaissance must be carried out to assess the suitability of the selected test sites. Reconnaissance is done by physically examining the network to establish which mains and junctions in the network are actually accessible for testing purposes. Accessible mains and junctions then define the sample space from which field measurements can be taken.

Additionally, during reconnaissance the modeller should establish under what conditions pump operators turn on a pump, and under what conditions valves are opened or closed. There is also need to establish which facilities represented in the model are actually operational. It is necessary to establish whether some facilities are off-line for maintenance or repair.

In general, international proposed guidelines stipulate that for a medium to highly detailed network model (medium to low skeletonisation), the following limits should be adopted (AWWA, 1999):

- 5% of nodes in the network should be tested for pressure readings
- 3% of the pipes in the network should be tested for flow readings.

2.5.2.5 Micro-calibration fine-tuning

Micro-calibration seeks to minimise an objective function while simultaneously satisfying constraints that describe the feasible calibration solution (Walski *et al.*, 2003). The objective can be either to *minimize the sum of difference squares*, or to *minimize the sum of absolute differences*, or to *minimize the maximum absolute difference*, between the field values and the model-generated values (Zheng *et al.*, 2002). For this research, the default objective function of the chosen modeling package (WaterCAD) was selected. This package's default calibration function minimizes the sum of the squares of differences between observed and model-predicted heads and flows. The equation to compute the objective function is provided here below:

$$Minimise\quad \frac{\sum_{np=1}^{NH} W_{nh}\left(\frac{Hsim_{nh}-Hobs_{nh}}{Hpnt}\right)^2+\sum_{nf=1}^{NF} W_{nf}\left(\frac{Fsim_{nf}-Fobs_{nf}}{Fpnt}\right)^2}{NH+NF}$$

(Equation 2.4: Haestad, 2002)

Where: $Hobs_{nh}$ designates the nh-th observed hydraulic grade. $Hsim_{nh}$ is the nh-th model simulated hydraulic grade. $Hloss_{nh}$ is the head loss at observation data point nh, $Fobs_{nf}$ is the observed flow, $Fsim_{nf}$ is model simulated flow, Hpnt notes the hydraulic head per fitness point, while Fpnt is the flow per fitness point. NH is the number of observed hydraulic grades and NF is the number of observed pipe discharges, W_{nh} and W_{nf} represent a normalized weighting factor for observed hydraulic grades and flows respectively. They are given as: $W_{nh} = f(Hloss_{nh} /\Sigma Hloss_{nh})$, Wnf = $f(Fobs_{nf} /\Sigma Fobs_{nf})$. And f ( ) is a function which can be linear, square, square root, log, or constant.

The model fine-tuning process is an extremely laborious task when attempted manually. However, over the last two decades, several approaches have been proposed which use optimization techniques for model calibrations to arrive at a relatively accurate calibration solution; the most prominent being the use of genetic algorithms (Zheng *et al.*, 2004). This technique was adopted in the model construction for this research, and is a value-added component of the selected software package – WaterCAD (Bentley, 2006; CH2M HILL, 1999).

Genetic algorithm (GA) is a robust search calibration optimisation paradigm based on the principles of natural evolution and biological reproduction (Goldberg, 1989, cited in Zheng *et al*., 2002). In this technique, a genetic algorithm program first generates a population of trial solutions of the model parameters. A hydraulic network solver program then simulates each trial solution. The resulting hydraulic simulation predicts the HGL (junction pressures) and pipe flows at a predetermined number of nodes (or data points) in the network. An associated calibration module then evaluates how closely the model simulation is to the observed data, the calibration evaluation computes a "goodness-of-fit" value, which is the discrepancy between the observed field data and the model predicted data, for each solution. This value is then assigned as the "fitness" for that solution in the genetic algorithm.

One generation produced by the genetic algorithm is then complete. The fitness measure is taken into account when performing the next generation of the genetic algorithm operations. To find the optimal calibration solutions, fitter solutions are selected by mimicking Darwin's natural selection principal of "survival of the fittest". The selected solutions are used to reproduce a next generation of calibration solutions by performing genetic operations.

Over many generations, the solutions evolve, and the optimal or near optimal solutions ultimately emerge. Optimised calibration is thus arrived when model parameters are calculated by using a genetic algorithm while minimizing the selected objective function and satisfying the calibration constraints (Haestad, 2002).

Internationally acceptable levels of accuracy have been documented and published by AWWA (*see Table 2*). These guidelines were adopted for this study. However, as noted in the problem statement of this research, while they have been widely adopted for practical use, these guidelines are not globally accepted as standards, and thus require validation for suitability to the local situation, (Walski *et al.*, 2003), which is one of the major goals of this study.

Table 2*: Proposed Calibration criteria for flow and pressure (AWWA, 1999)*

Flow Criteria
(1) Modelled trunk main flows (where the flow is more than 10% of the total demand) should be within ±5 % of the measured flows.
(2) Modelled trunk main flows (where the flow is less than 10% of the total demand) should be within ±10 % of the measured flows.
Pressure Criteria
(1) 85% of field test measurements should be within ±0.5 m or ±5 % of the maximum head loss across the system, whichever is greater.
(2) 95% of field test measurements should be within ±0.75 m or ±7.5 % of the maximum head loss across the system, whichever is greater.
(3) 100% of field test measurements should be within ±2 m or ±15 % of the maximum head loss across the system, whichever is greater.

2.5.2.6 EPS Calibration

Before beginning the calibration of an EPS model, the user needs to be confident that the steady-state model is calibrated correctly in terms of elevation, spatial demand distribution, and pipe roughness.Once calibration on that level is achieved, the EPS calibration procedure can begin and consists primarily of the temporal adjustment of demands. The focus of this research was evaluation of the spatial consistency of accuracy levels of a given hydraulic model. EPS calibration was therefore beyond the scope of methodology required.

2.5.3 Establishing Objectives and Model Application

Prior to applying the model, the specific modelling objectives should be clearly established. The objectives may include specification of particular water demand and operational modes. Based on these specifications, a series of scenarios can be defined and the model applied appropriately. Some software products contain a scenario manager that helps the user to define and manage a large number of specific model runs. Additional scenarios can be developed in order to test the sensitivity of the system to variations in model parameters that are not known with certainty.

2.5.4 ANALYSIS AND DISPLAY OF RESULTS

Water distribution system models generate a large amount of output. The amount of calculated information increases with increasing model size and, for EPS, the duration of the model run. Modern water distribution system analysis software typically provides a range of graphical and tabular displays that help the user wade through the large amount of output data so that it may be efficiently analyzed. These outputs represent a small subset of types of graphics generated by most modelling software. The output should be analyzed to ensure that the model is operating properly and to extract the information required in order to analyze the specific problem being studied.

2.6 HYDRAULIC MODELLING SOFTWARE

A variety of software packages are available to perform hydraulic modelling. A majority of these packages utilize the EPANET formulation as the basic computation engine (USEPA, 2005). The following subsections briefly describe the EPANET model and summarize the features of other available software, particularly WaterCAD by Haestad Methods.

2.6.1 EPANET SOFTWARE

EPANET was initially developed in 1993 as a distribution system hydraulic-water quality model to support research efforts at EPA (Rossman, 2000). The development of the EPANET software also satisfied the need for a comprehensive public-sector model and has served as the hydraulic and water quality “engine” for many commercial models. EPANET can be used for both steady-state and EPS hydraulic simulations. In addition, it is designed to be a research tool for modelling the movement and fate of drinking water constituents within distribution systems. EPANET can be operated in the SI (metric) or British systems of measurement. Outputs from EPANET include: colour-coded network maps, time series plots, and tabular reports.

In addition to the standard use of EPANET in a Windows environment using the graphical user interface (GUI), the functionality of EPANET can be accessed through the EPANET toolkit. The toolkit is a series of open source routines available in both Visual Basic and C (programming language) that can be used as is or modified and accessed from a user’s own computer program. This powerful capability has been widely used throughout the world to support both research and specific applications in the field of water distribution system analysis.

Although EPANET is a freely available, public-domain software, whose source code can be readily accessed for specialised application development, never-the-less this research employed a commercially available package, namely, *WaterCAD*.

Being the "engine", EPANET has limited applicability to practical water distribution network operation and model development. Commercially packages such as WaterCAD, provide enhanced value-added capabilities that are vital for the practical and economically-feasible simulation of water distribution networks. These are highlighted in the following section.

2.6.2 COMMERCIAL HYDRAULIC-WATER QUALITY MODELLING SOFTWARE - WATERCAD

In addition to EPANET, there are several commercial software packages that are widely used internationally. Most of these packages are based on the EPANET formulation and include value-added components as parts of GUI that increase the capability of the software. Examples of such value-added components that are part of one or more of the commercially available software packages include:

- *Scenario manager*: Manage inputs and outputs of a group of model runs.
- *Calibration optimization*: Utilize genetic algorithm optimization technique to determine model parameters that best fit a set of field data.
- *Design optimization*: Utilize genetic algorithm optimization techniques to select pipe sizes that minimize costs or other selected objectives.
- *Integration with GIS or CAD*: Water distribution model directly integrates with GIS or CAD to assist in constructing or updating model and display results.
- *Flexible output graphics*: Provides convenient ways to modify parameters for graphical displays of output data.
- *Energy management*: Calculates energy use for a selected alternative.
- *Automated fire-flow analysis*: Assesses the availability of fire flow at a range of nodes and determines whether a system meets fire-flow requirements.
- Water security and vulnerability assessment methods, skeletonisation, and demand allocation tools.

Major commercial software includes; WaterCAD by Haestad Methods, MIKENET, WESNET, INFOWORKS, SYNERGEE, WATNET, HARP, and H2ONET hydraulic modelling packages.

WaterCAD by Haestad Methods

For the purposes of this study, WaterCAD software was selected because of its ready-availability, and its several advantages including (Bentley, 2006; CH2M HILL, 1999);

- Seamless compatibility with leading GIS packages (ESRI), facilitating powerful GIS Geo-data handling and real-time access to up-to-date network information.
- Advanced Optimisation techniques i.e. Genetic Algorithm (GA) utilisation, Darwin Calibration, Scenario management, Darwin Designer etc. and
- Advanced Capability i.e. diagnostic capabilities, identifying potential or existing problem areas, conducting fire flow, and water quality assessments throughout the system

2.7 LARGE SCALE HYDRAULIC MODELLING IN UGANDA

As noted in the first chapter, the adoption of hydraulic modelling technology in Uganda is still in its infancy. The largest and most complex water systems exist in the Capital City, Kampala. Liaison with the City's water utility revealed that there are no large-scale low-skeletonisation models of the network. The closest attempt was a highly skeletonised model of the system constructed as part of consultations on the design of the third water treatment plant (KW GIS Office, 2008). Given this situation, this research would essentially pioneer the deployment of hydraulic simulation technology at such a scale.

2.7 CONCLUSION

This literature review identified and discussed hydraulic theory, model input characterisation, model selection and application, hydraulic modelling software, and model calibration as the key considerations for successful hydraulic simulation. Important observations from the review included the application in hydraulic simulation of the *fundamental equations* for hydraulic analysis, noting the Hazen-William's Head Loss Equation (the formula adopted for this study) as the most prominently used. In discussing the possible model inputs and skeletonisation; low skeletonisation – though demanding – was identified as ideal for detailed analysis. Additionally, GA optimisation was identified as the most practical calibration technique for large-scale modelling given the rigours and inefficiencies of manual model calibration. These observations and concepts formed the backbone of the modelling exercise.

Subsequent chapters illustrate methodologies and activities derived from these considerations, which were used to construct the model and perform the required accuracy analysis.

CHAPTER THREE

3.0 METHODOLOGY

The presentation of the methodology that follows indicates how the specific objectives presented in Chapter 1 were achieved in this research. The outcome of the Literature forms the background of the methodology used – i.e. supplies all technical theory that is required. Each of the subsections indicates the sub-objective and the associated methodology.

3.1 IDENTIFICATION OF THE UTILITY'S HYDRAULIC MODELLING NEEDS

Prior to the actual construction of the hydraulic model, it was necessary to develop consensus within the water utility regarding the need for the model and the short and long-term purposes for which the model would be used (Walski *et al.*, 2003). This required envisioning of the top management and staff through *discussions*; to ensure adequate sensitisation and secure the involvement of personnel at all pertinent levels during the model construction process. A *desk study* of the utility's operational and management documents, was also done to discover the utility's priorities and hence the best paradigm for the hydraulic modelling process.

Although the model constructed in this study was intended for research purposes, it was anticipated that the outcome of the research would provide sufficient impetus for the subsequent propagation of hydraulic modelling technology for the entire City's water network. For the model to have practical relevance upon completion of the research, it was important for it to be constructed based on the utility's actual requirements. Using the methodology stated above, a clear understanding of the purposes of the modelling was obtained. This in turn provided a strategic direction to the process of developing the hydraulic simulation of the water distribution network.

3.2 MODEL CONSTRUCTION

Given the nature of the research, the model was constructed to simulate base/normal network operation conditions. The construction process began with assembling the required data to populate the model. Data required included; the geographic configuration of the network mains, the geo-spatial distribution of demands, physical element attributes and other relevant data. This required a *desk study* of the GIS archives and database records of the utility company. Data collection also required *interviews* with the custodians of the necessary data such as pump attendants, GIS personnel, and other technical personnel at the utility.

It was also necessary to conduct a concurrent, in-depth training of the chosen hydraulic modelling package (in this case WaterCAD), through a *comprehensive desk study* of existing literature and on-line courses. With sufficient knowledge about the workings of the selected modelling package, the data obtained from the utility's GIS archives was then appropriately entered into the model.

3.2.1 NETWORK FEATURES

Through the desk study, CAD based maps of the Naguru supply area were obtained. Line features in the CAD maps were converted into polylines in DXF format, which were then imported into the hydraulic modelling package. The spatial attributes of node blocks in the CAD drawings (including control and system valves, junctions, tank locations, etc.) were also exported to an MS Excel sheet from where they were transferred into WaterCAD.

3.2.2 FEATURE ATTRIBUTES

The hydraulic and physical attributes of the features in the network were obtained from GIS databases obtained from the utility's GIS office. By synchronising the imported WaterCAD network with these external databases, the attributes of each of the features was imported into the model. As indicated in the literature review, skeletonisation of the model's network was limited to mains with nominal diameters greater or equal to *50mm* as per the GIS data.

The network's topology was obtained from CAD contours obtained from the utility's GIS office as indicated in Section 2.4.3 of this dissertation. Using these contours the elevations of all the nodes in the network were computed using manual interpolation, and assigned accordingly.

The computation and allocation of demands in the network for its base/normal/existing state was achieved using customer-meter aggregation for revenue water (billed volumes), and flow distribution for non-revenue water (*see section 2.4.2.1*).

The process required the generation of *demand polygons* for each node in the network, extracting the customers in each polygon, and assigning them to the appropriate network node. Each customer on the utility's CAD maps has a Property Reference (PR) number, which is a unique identification number with a corresponding customer reference number in the utility's billing database.

Using these PR's, the annual consumption records for each customer were extracted from the billing system. The base demand for each node was then computed as the total average monthly demand for all customers assigned to that node expressed in litres per second.

The average annual NRW percentage was computed from the records obtained from the utility's operations report (NWSC, 2007). Non-revenue water was assigned as a percentage of the base-line demand using the flow distribution method, ensuring that the total demand from the source reservoir matched with the physically recorded values.

The objectives of this research implied that the seasonal and climatic temporal variability of demands were not relevant. A typical diurnal composite demand curve consisting of a sequence of demand multipliers was developed for the network and assigned to the nodal demands. This demand curve was approximated from reservoir level observations and data logged flow tests at the reservoir outlet (Walski *et al.*, 2003).

Having defined the network features, attributes, and demand allocations, preliminary simulations were then performed using the model to analyse the sufficiency of the data parameters and eliminate gross errors within the model.

3.3 CALIBRATION, VALIDATION AND VERIFICATION OF THE MODEL

Model calibration is "the process of adjusting model parameter data (or, in some cases, model structure) so that the simulated hydraulic and water quality output sufficiently mirrors observed field data" (USEPA, 2005). In this study, internationally proposed calibration guidelines were adopted as elucidated in the literature review. The selected methodology is highlighted in subsequent sections.

3.3.1 THE SAMPLE DESIGN PROBLEM

Model calibration required the collection of several datasets of flow quantities and pressure at various selected locations within the physical network. To achieve this, a *sampling design problem* (limiting sampling criteria) for the constructed model was developed – as indicated in the literature review – and the requisite field test points selected. This necessitated the selection of the appropriate minimum distance, discharge and pressure as the limiting constraints to the random sampling procedure (Kapelan, 2003). The actual values defining the model's sample design problem are indicated in the following chapter.

The resulting *sampling frame* consisted of list of network pipes and a list of network nodes (junctions) both arranged in ascending order based on their feature identification numbers (ID).

3.3.2 TEST-LOCATION SAMPLING

Having developed the sampling design problem defining the limiting constraints for the sampling frame, *systematic random sampling* was done to obtain two distinct sets of field measurements. The first set of test locations (1 dataset) were used as calibration datasets. The second set of hydraulic field measurements consisted of two (2) extra post-calibration datasets for the accuracy-consistency assessment.

The sizes of samples selected for the study were 3% of all the network pipes, and 5% of all the network junctions, as indicated in the literature review. Test-location sampling for the different datasets was done without replacement to ensure that locations were unique in each dataset. This enabled maximum spatial diversity in the assessment of the model's performance. The sampling interval, k, was calculated as:

$$k = \text{population size } (N) / \text{sample size } (n) \qquad \text{(Equation 3.1)}$$

3.3.3 MACRO-CALIBRATION AND RECONNAISSANCE

The macro-calibration process identified and eliminated large anomalies in the model's performance. Anomalies rectified included; discontinuities in the pipe configuration (broken lines, incomplete loops etc.), incorrect valve statuses (non existent PCV's, throttled valves etc.), and abnormal demand allocations. Some of the key pointers used to locate these anomalies, as mentioned in the literature review (Section 2.5.2.1), were pipes with flow velocities greater than 1.5m/sec, head losses greater 10m per kilometre, and large diameter pipes with head losses greater than 3m per kilometre.

Reconnaissance was then carried out to assess the suitability of the selected test sites. Reconnaissance was done by physically examining the network to establish which mains and junctions in the network are actually accessible for testing purposes. Accessible mains and junctions then formed the required sets of test-locations from which field measurements could be taken. Test-locations that were discovered to be inaccessible were replaced with adjacent suitable locations. Where this was not possible, new locations were identified by continuing the *systematic sampling* process, and subjecting them to the reconnaissance assessment for suitability. This process was continued until the required sets of test-locations were obtained.

The reconnaissance survey also revealed pertinent information concerning pump and valve operations, and the operational status of the facilities represented in the model. It was necessary to establish whether some facilities were off-line for maintenance or repair.

Having verified the selected test-locations for the 3 datasets required for the research, and synchronised the model's network operation with the actual network operation, field testing was then carried out starting with the calibration/control dataset. The 2 post-calibration datasets were then collected accordingly.

As highlighted in the literature review, *EPS calibration* was beyond the scope of this study. Consequently, although an EPS model was constructed to satisfy the anticipated, post-research model application objectives; calibration was only required for the steady-state, base-demand condition. To achieve this, only results corresponding to the base demand scenario (diurnal curve multiplier = 1) were selected from the collected data-logged test results, for use in the micro-calibration and subsequent stages of the study.

3.3.4 MICRO-CALIBRATION

The WaterCAD Darwin Calibrator based on genetic algorithm optimisation, was used to synchronise the model's output with the field observed network performance to the required level of accuracy.

The use of genetic-algorithm optimisation for network calibration is discussed in detail in Chapter 2 of this thesis. The acceptable level of accuracy was determined based on the AWWA published guidelines as indicated in the literature review. The objective function used for this research was to *minimise the sum of the squares* of differences between observed and model-predicted heads and flows, which is the default function of the selected modelling package.

3.4 EVALUATION OF THE CONSISTENCY OF MODEL ACCURACY

Having completed the calibration of the constructed network model for the Naguru water supply area, the consistency of the model generated hydraulic parameters through out the network was then evaluated.

Using the 2 post-calibration dataset field measurements, the levels of accuracy achieved by the model for each dataset were computed, using the ‘WaterCAD Darwin Calibrator’ tool. The same objective function utilised for the calibration phase, was employed for this computation. The computed “goodness-of-fit” values of the objective function given the post-calibration test results were then compared with those obtained at the calibration phase.

This facilitated the performance of a comparative analysis between the accuracy levels attained at the calibration and those recorded from the post-calibration experimental surveys. Analysis results were then used as a basis for recommendations on the suitability of the hydraulic model construction and calibration guidelines (adopted from internationally suggested guidelines), given the local context.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

The methodology employed in the construction and calibration of the water distribution network model for the Naguru supply network was illustrated in the previous chapter. The results generated at each stage of that process form the contents of this chapter. Notable milestones include; the adoption of a strategic network modelling perspective, the selected hydraulic model parameters, the calibration parameters and computations, and the post-calibration comparative analysis.

4.1 STRATEGIC NETWORK MODELLING PERSPECTIVE

The adoption of a strategic hydraulic simulation paradigm was governed largely by the purpose of the research. One of the anticipated by-products of this research was to establish a tentative benchmark for the further propagation of the technology within Kampala City and the entire country. The modelling paradigm therefore required the utilisation of model construction and calibration guidelines that result in the greatest possible coverage area, highest possible network complexity, greatest control and accuracy.

Fortunately, upon consultation with the utility's top management and staff through various discussions, the utility's interests were found to be congruent with the research perspective. This desire was adequately captured in the utility's Business Plan 2006-2008; expressed as to develop

> "…a distribution network model for day to day management of the system (mains extensions, leakage control, establish potential water supply failures, identify operational changes & distribution improvements) and capital planning – 'System Optimisation'…" (NWSC, 2006).

This outlook required the development of network modelling functionality for immediate-term routine network operation and intensification, medium-term network extensions, and the ultimate long-term network growth planning. The utility therefore desired a model that covers the entire City's water supply network, provides technical staff with the greatest possible control and accuracy, all at a feasible cost. However, because of the resource limitations in a developing country; while the model developed would be as detailed and accurate as possible, it would not be feasible to include all the finer details of the water distribution network, and perform network validation using specialised tests (e.g. fire flow tests).

In this light, the compromise strategic direction arrived at for the study was one summed-up as '*low-skeletonisation, large-scale*' network simulation. The research thus elected to commence with the Naguru area network model as a prototype for the subsequent development of a City wide model. This criterion ultimately governed the demarcation of the study area, model construction methodology, the skeletonisation philosophy, and the subsequent calibration methodology as indicated in previous chapters of this thesis.

4.2 MODEL CONSTRUCTION

The model construction process necessitated importing of DXF drawings and the Contour layers used to define the feature elevations into the model. Excerpts of the tables of the node coordinates used to construct the model, hydraulic and physical network attribute data, processed junction demands, and utilised typical diurnal curve are provided in Appendix I of this dissertation. Extensive data on these components, including the complete tables, is with the author. The entire model building process is summarised in table 3 below. In addition, extracted samples of drawings and tables corresponding to each stage summarised in table 3, are respectively provided in Appendix I.

Table 3: *Model construction stages, activities and results.*

MODEL CONSTRUCTION PROCESS/STAGE	ACTIVITIES CARRIED OUT	CORRESPONDING RESULTS TABLES/SCREEN-SHOTS
• Development of the basic network model.	• CAD to DXF drawing conversions • Database-to-model synchronisation • Billing data analysis and meter-aggregation demand allocation • NRW demand flow-distribution allocation	• Figure A1-2, Figure A1-3 • Figure A1-4 • Figure A1-5, Figure A1-6, Figure A1-7 • Table 4
• Model Calibration	• Macro-calibration (general debugging) • Micro-calibration (sampling, testing, G.A. optimised calibration and analysis	• Figure A1-8, Figure A1-9 • Table 5, Table 6
• Results analysis and display.	• Re-sampling and testing • G.A. optimised calibration and analysis	• Table 7, Table 8, Table 9, Table 10

NRW Computation

Average Annual NRW percentage for the year 2007 was computed as indicated in Table 4 below;

Table 4: *Average KW NRW percentage for the year 2007 (Source: KW NRW, 2007)*

Month of 2007	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	**AVG**
NRW %age	46.4	38.1	41.1	38.7	41.9	38.1	38.2	38.1	37.8	48	46.7	46.4	**41.625**

Using the Flow Distribution Technique of demand allocation, the following computations applied for NRW demand at each of the network junctions, when the Billed Consumption is known;

Consumption Demand Percentage (CD %) = 100% – NRW Percentage (NRW %) *(Equation 4.1)*
Thus, CD % = 100% – 41.6% = 58.4%

Total Demand, TD (l/s) = Consumption Demand, CD (l/s) / CD % *(Equation 4.2)*
Thus, TD (l/s) = CD (l/s) / CD % = TD (l/s). That is, TD (l/s) = CD (l/s) / 58 %

But NRW Demand at each node (l/s) = TD (l/s) – CD (l/s) *(Equation 4.3)*
Thus, NRW Demand at each node (l/s) = (CD (l/s) / 58.4%) – CD (l/s) *(Equation 4.4)*

NRW Demand was then allocated to each junction according to Equation 4.4.

4.3 MODEL CALIBRATION

This section details all the criteria that were used in calibrating the network model, and the results of the calibration process.

Model Sample Design Problem

Parameters selected for the model's sample design problem were as follows:

- Minimum distance: 2km from Naguru Main Reservoir
- Minimum Discharge: 5 l/s
- Minimum Pressure: 3 bars (300kPa)

The lists of pipes and nodes that formed the sampling frame for the calibration test locations are attached in Appendix II of this thesis.

Calibration Sample Size Computation

(See Appendix II for tables of the actual sampling process)

Pipes:

- Total number of pipes in the network = 605 pipes
- Number of pipes in sample space having applied limiting conditions = 84 pipes
- However, minimum acceptable sample = 3% of all pipes in the network
- Sample size = 0.03 x 605 = 18.15 which is approximately 20 pipes
- So 20 pipes were tested in the Naguru network
- Systematic Sampling Interval, k = 84/20 = 4.2. Thus k is approximately 4

Junctions:

- Total number of junctions in the network = 422 junctions
- Number of junctions in sample space having applied limiting conditions = 86 junctions
- However, the minimum acceptable sample = 5% of all the junctions in the network.
- Hence, sample size = 0.05 x 422 = 21.1 which is approximately 22 junctions
- So 22 junctions were tested in the Naguru network
- Systematic Sampling Interval, k = 86/22 = 3.91. Thus k is approximately 4

Optimised Micro-calibration

Several images have been appended to this dissertation describing the location of sampled calibration test-sites and micro-calibration using the Darwin Calibrator (*Refer to Table 3: Model construction stages, activities and results, and Appendix 1*).

The recorded data from the calibration field tests (*refer to Appendix II – Calibration Dataset*) was loaded into the model and micro-calibration was carried out using the Darwin calibrator. The model's "goodness-of-fit" was improved from 368,116,832 (*see Figure 17 above*) to 3909.337. Beyond this point the specified maximum number of trials the GA can perform without improvement (selected as 10,000) was exceeded.

4.3.1 MODEL ACCURACY

The simulated behaviour of the calibrated water network model is captured in *Appendix II, Tables A2-1 and A2-2*. Using the AWWA proposed guidelines for acceptable levels of accuracy (*see Table 2)*; the model's accuracy was evaluated as indicated below:

Simulated Flow Accuracy

10% of total demand = (140.67*0.1) = 14.067 l/s. Comparing Simulated Discharge and Observed Discharge with internationally proposed guidelines (Table 5 below);

Table 5: Model Flow Verification

Pipe	Observed Discharge (l/s)	Modelled Discharge (l/s)	%age Error	Satisfactory? (< 5%?)	Satisfactory? (< 10%?)
P-3206	21.09	25.41	20.48	No	
P-1999b	15.37	21.52	40.01	No	
P-2000a	20.72	16.94	18.24	No	
P-2639b	27.27	15.91	41.66	No	
P-2003b	8.64	10.54	21.99		No
P-2004b	7.56	9.6	26.98		No
P-1956	10.65	9.48	10.99		No
P-2774b	9.33	9.39	0.64		Yes
P-1989a	8.75	8.53	2.51		Yes
P-1961	6.14	7.73	25.90		No
P-3287	6.48	7.25	11.88		No
P-2644	4.13	5.3	28.33		No
P-1987b	9.38	5.17	44.88		No
P-2876a	8.21	4.59	44.09		No
P-3207	4.53	4.02	11.26		No
P-3237	1.37	0.9	34.31		No
P-3224	0.81	0.85	4.94		Yes
P-1969a	5.28	-6.7	26.89		No
P-2869d	12.06	-9.77	18.99		No
P-2869f	9.84	-13.02	32.32		No
%age Compliance =				***0%***	***19%***
Average Modelled Flow Accuracy =			***23%***		

Simulated Pressure Accuracy

Maximum simulated head-loss across the system = 16.62 m. Comparing Simulated Pressure and Observed Pressure with proposed guidelines (Table 6 below); The Pressure Limits are;

- *Category 1:* 0.05 of 16.62 = 0.831m, which is greater than 0.5m, thus;
  Atleast 85% of simulated results should be within ± 0.831m of the observed results
- *Category 2:* 0.075 of 16.62 = 1.2465m, which is greater than 0.75m, thus;
  Atleast 95% simulated results should be within ± 1.237m of the observed results
- *Category 3:* 0.15 of 16.62 = 2.493m, which is greater than 2m, thus;
  100% simulated results should be within ± 2.493m of the observed results

Table 6: Model Pressure Verification

Node	**OP (kPa)**	**OP (m)**	**Simulated Pressure (kPA)**	**Simulated Pressure (m)**	**Abs (OP - SP)**	**%age Error**	**OK? (<0.831m?)**	**OK? (<1.237m?)**	**OK? (<2.493m?)**
J-2923	370	37	373.64	37.36	0.364	0.98	Yes	Yes	Yes
J-2926	390	39	400.37	40.04	1.037	2.66	No	Yes	Yes
J-3080	550	55	569.1	56.91	1.91	3.47	No	No	Yes
J-3113	660	66	673.54	67.35	1.354	2.05	No	No	Yes
J-3190	630	63	620.86	62.09	0.914	1.45	No	Yes	Yes
J-3192	645	64.5	648.04	64.80	0.304	0.47	Yes	Yes	Yes
J-3247	260	26	261.63	26.16	0.163	0.63	Yes	Yes	Yes
J-3272	500	50	509.56	50.96	0.956	1.91	No	Yes	Yes
J-3289	780	78	790.14	79.01	1.014	1.30	No	Yes	Yes
J-3313	55	5.5	89.74	8.97	3.474	63.16	No	No	No
J-3327	890	89	883.89	88.39	0.611	0.69	Yes	Yes	Yes
J-3770	640	64	651.56	65.16	1.156	1.81	No	Yes	Yes
J-3775	320	32	327.86	32.79	0.786	2.46	Yes	Yes	Yes
J-3786	700	70	791.79	79.18	9.179	13.11	No	No	No
J-3828	710	71	743.87	74.39	3.387	4.77	No	No	No
J-3834	470	47	410.39	41.04	5.961	12.68	No	No	No
J-3841	500	50	532.15	53.22	3.215	6.43	No	No	No
J-3847	520	52	508.43	50.84	1.157	2.22	No	Yes	Yes
J-3854	805	80.5	781.49	78.15	2.351	2.92	No	No	Yes
J-3862	550	55	592.92	59.29	4.292	7.80	No	No	No
J-3879	430	43	459.18	45.92	2.918	6.79	No	No	No
J-3886	535	53.5	551.33	55.13	1.633	3.05	No	No	Yes
%age Compliance =							***23%***	***50%***	***68%***
Model Pressure Accuracy =						***6%***			

Discussion

The average percentage error of the simulated flow parameters compared with the physical network was about 23%. This reveals that whilst the model calibration process reached its logical conclusion, the accuracy level achieved was still relatively low. International guidelines indicate that the desirable accuracy should be between 5–10 percent for flow measurements. Probable sources of this large discrepancy are diverse (Walski, 1990 cited in Walski *et al.*, 2003). Any and all input data that have uncertainty associated with them are candidates for adjustment during calibration to obtain reasonable agreement between model-predicted behaviour and actual field behaviour. A discrepancy found during the calibration process could also mean that the system itself has problems. AWWA provides for several sources of error in the model simulation which could be categorised in this dissertation as either model structural or model input error sources (AWWA, 1999).

Model structural errors include modelling detail (skeletonisation errors) and geometric anomalies. As mentioned in Section 2.3, differences in the hydraulic formula used are generally insignificant and can therefore be considered inconsequential as far as simulation errors are concerned (USEPA, 2005, Walski *et al.*, 2006). Skeletonisation errors are often difficult to identify, while geometric anomalies are normally easily identified and eliminated during macro-calibration (AWWA, 1999).

Model input error causes could include typographical errors, measurement errors, pipe-roughness value approximation errors, compensating errors, demand allocation errors, etc. Further research could be necessary to establish which one(s) of these is the largest contributor to this discrepancy. Recommendation to that effect is made in the next chapter. Even so, upon review of the model construction process several insights can be deduced. First, the probability that typographical errors occurred is quite low, since such errors would likely have been identified at the macro-calibration stage. Measurement errors are more likely given the human factor; while pipe roughness value errors are relatively unlikely given the limited range of values and their nearly standardised nature.

Demand allocation errors are most likely the main sources of error, which could be deduced from the relatively low flow accuracy values. Reliance on often inaccurately measured billing records (due to metering age, mechanical faults etc.), and the use of the less accurate flow distribution method for NRW demand allocation could have been the main causes of simulation error (Savic *et al.*,2009). Nevertheless, further research is necessary to verify these assertions.

Estimated percentage error of simulated pressures was 6% which could be deemed satisfactory. It was also noted that the pressure accuracy was better than flow accuracy. The rationale for this could be found in the differences in computation procedures for the two parameters. Pressure is governed only by the elevation of the given junction and the head-loss incurred within the system. Elevation values are generally highly accurate, while frictional head-losses are relatively diminutive compared to the gravity head; *average head-loss* = 0.46m, while *average pressure head* (ignoring negative pressures) = 58.5m. Discharge simulation accuracy, on the other hand, is directly affected by the highly variable nature of consumption demands and network operation. Further study could be done to verify this assertion. A recommendation concerning this is also made in the next chapter.

Considering the international guidelines on model accuracy, both flow and pressure parameters were found to be incompliant. None of the pipes with discharge greater than 14.07 l/s were within the 5% acceptability limit, while only a few (19%) of the pipes with discharge less than 14.07 l/s were within the acceptability limit of 10% (*see Table 5 above*). Similarly, the limits of 85%, 95% and 100% for pressure accuracies were all not achieved.

It was therefore observed that these limits were quite stringent, requiring very high model accuracy levels, which were evidently not achieved as noted earlier. Never-the-less, with further analysis of the error patterns in the system as recommended earlier, these limits should be achievable.

In addition, these limits do not reflect that the model's pressure accuracy (6%) seems relatively acceptable for most utilities' hydraulic simulation requirements. This implies that the model's pressure simulations would be incorrectly disqualified basing on these guidelines. The internationally proposed guidelines for pressure are therefore found to be unnecessarily stringent, and could be streamlined to reflect these findings.

A structure catering for different accuracy level requirements could be more appropriate for simulated pressures. For instance, the existing guidelines could be restricted to situations where only accuracies less than 5% are acceptable. Less stringent guidelines would then apply of acceptable accuracies between 5% - 10%, 10% - 15% and so on.

4.4 POST CALIBRATION

The recorded data from the post-calibration (PostCal) field tests (*refer to Appendix II – PostCal Dataset 1 & 2*) was loaded into the model and the fitness computed with the Darwin calibrator. The model's "goodness-of-fit" values were obtained as 5163.67 and 5927.3.

4.4.1 POST-CALIBRATION MODEL ACCURACY

The computation of fitness values for the water network model for both Post-calibration datasets is captured in *Appendix II*. Using the AWWA proposed guidelines for acceptable levels of accuracy (*see Table 2)*; the resulting accuracy was evaluated as indicated below:

Simulated Flow Accuracy – Post Calibration Dataset 1

10% of total demand = (140.67*0.1) = 14.067 l/s

Comparing Simulated and Observed Flow with the proposed guidelines (Table 7 below);

Table 7: Model Flow Accuracy given Post-Calibration Dataset 1

Pipe	Observed Discharge (l/s)	Modelled Discharge (l/s)	%age Error	OK? (< 5%)	OK? (< 10%)
P-3201	27.43	26.25	4.29	Yes	
P-3304	22.41	21.33	4.81	Yes	
P-1999a	22.17	20.6	7.07	No	
P-2001	16.58	15.64	5.65	No	
P-2002b	14.31	13.82	3.39		Yes
P-2640c	15.21	13.42	11.74		No
P-2640a	15.56	13.42	13.76		No
P-1945a	13.18	13.38	1.55		Yes
P-1946b	13.09	13.34	1.94		Yes
P-2641b	13.08	11.9	9.01		Yes
P-2643a	12.44	11.25	9.59		Yes
P-1952	9.92	10.73	8.19		Yes
P-2003c	10.12	10.33	2.08		Yes
P-1954	9.18	9.51	3.63		Yes
P-2643b	10.01	8.94	10.67		No
P-1989a	7.95	8.53	7.26		Yes
P-2776e	7.39	7.97	7.88		Yes
P-2776g	4.42	4.87	10.18		No
P-3293	1.15	0	100.00		No
P-2869e	11.54	-10.87	5.81		Yes
P-1948	10.40	-11	5.80		Yes
%age Compliance =				**50%**	**71%**
Model Flow Accuracy =			**11%**		

Simulated Pressure Accuracy – Post Calibration Dataset 1

Maximum Simulated Head-loss across the system = 16.62 m

Maintaining the same pressure limits as prescribed by international guidelines, and comparing Simulated Pressure and Observed Pressure with proposed guidelines (Table 8 below);

Table 8: Model Pressure Accuracy given Post-Calibration Dataset 1

Node	OP (kPa)	OP (m)	Simulated Pressure (kPA)	Simulated Pressure (m)	Abs (OP - SP)	%age Error	OK? (<0.831m?)	OK? (<1.237m?)	OK? (<2.493m?)
J-2849	720	72	707.22	70.72	1.278	1.77	No	No	Yes
J-2920	350	35	354.29	35.43	0.429	1.23	Yes	Yes	Yes
J-2925	420	42	420.48	42.05	0.048	0.11	Yes	Yes	Yes
J-2961	420	42	416.67	41.67	0.333	0.79	Yes	Yes	Yes
J-2990	360	36	351.92	35.19	0.808	2.24	Yes	Yes	Yes
J-2990	350	35	351.92	35.19	0.192	0.55	Yes	Yes	Yes
J-3061	400	40	392.65	39.27	0.735	1.84	Yes	Yes	Yes
J-3083	380	38	379.36	37.94	0.064	0.17	Yes	Yes	Yes
J-3085	370	37	371.05	37.11	0.105	0.28	Yes	Yes	Yes
J-3273	500	50	490.14	49.01	0.986	1.97	No	Yes	Yes
J-3292	540	54	525.73	52.57	1.427	2.64	No	No	Yes
J-3344	570	57	576.39	57.64	0.639	1.12	Yes	Yes	Yes
J-3581	760	76	743.88	74.39	1.612	2.12	No	No	Yes
J-3763	600	60	603.93	60.39	0.393	0.65	Yes	Yes	Yes
J-3765	960	96	973.33	97.33	1.333	1.39	No	No	Yes
J-3783	700	70	693.99	69.40	0.601	0.86	Yes	Yes	Yes
J-3793	400	40	388.76	38.88	1.124	2.81	No	Yes	Yes
J-3814	660	66	664.02	66.40	0.402	0.61	Yes	Yes	Yes
J-3823	460	46	448.44	44.84	1.156	2.51	No	Yes	Yes
J-3861	550	55	557.24	55.72	0.724	1.32	Yes	Yes	Yes
J-3874	790	79	803.19	80.32	1.319	1.67	No	No	Yes
J-3894	670	67	656.83	65.68	1.317	1.97	No	No	Yes
%age Compliance =							**59%**	**73%**	**100%**
Model Pressure Accuracy =						**1%**			

Simulated Flow Accuracy – Post Calibration Dataset 2

10% of total demand = (140.67*0.1) = 14.067 l/s

Comparing Simulated Discharge and Observed Discharge with internationally proposed guidelines (Table 9 below);

Table 9: Model Flow Accuracy given Post-Calibration Dataset 2

Pipe	**Observed Discharge (l/s)**	**Modelled Discharge (l/s)**	**%age Error**	**OK? (< 5%)**	**OK? (< 10%)**
P-3302	32.99	27.38	17.01	No	
P-1998	31.71	22.57	28.82	No	
P-3305	23.33	21.06	9.73	No	
P-2639c	16.12	15.58	3.35	Yes	
P-2002a	12.38	15.18	22.62	No	
P-2003a	9.63	10.54	9.45		Yes
P-2775d	12.48	10.33	17.23		No
P-1953b	10.33	9.51	7.94		Yes
P-1958	6.59	8.99	36.42		No
P-2776c	8.42	8.78	4.28		Yes
P-2776b	6.72	8.78	30.65		No
P-3285	8.42	8.55	1.54		Yes
P-1963	9.77	6.42	34.29		No
P-2776f	5.28	4.87	7.77		Yes
P-1969b	4.31	-6.7	55.45		No
P-1972b	11.66	-10.96	6.00		Yes
P-1992b	9.69	-12.61	30.13		No
P-2868d	12.26	-13.22	7.83		Yes
P-1335a	12.34	-13.64	10.53		No
P-1990	12.44	-13.71	10.21		No
%age Compliance =				**20 %**	**47%**
Model Flow Accuracy =			**17%**		

Simulated Pressure Accuracy – Post Calibration Dataset 2

Comparing Simulated Pressure and Observed Pressure with proposed guidelines (Table 10 below);

Table 10: Model Pressure Accuracy given Post-Calibration Dataset 2

Node	OP (kPa)	OP (m)	Simulated Pressure (kPA)	Simulated Pressure (m)	Abs (OP - SP)	%age Error	OK? (< 0.831m?)	OK? (< 1.237m?)	OK? (< 2.493m?)
J-2921	610	61	501.05	50.11	10.895	17.86	No	No	No
J-2946	400	40	400.79	40.08	0.079	0.20	Yes	Yes	Yes
J-2966	300	30	357.98	35.80	5.798	19.33	No	No	No
J-3077	840	84	637.35	63.74	20.265	24.13	No	No	No
J-3079	460	46	452.4	45.24	0.76	1.65	Yes	Yes	Yes
J-3084	400	40	405.17	40.52	0.517	1.29	Yes	Yes	Yes
J-3282	810	81	793.01	79.30	1.699	2.10	No	No	Yes
J-3306	680	68	758.9	75.89	7.89	11.60	No	No	No
J-3764	410	41	594.32	59.43	18.432	44.96	No	No	No
J-3766	780	78	767.35	76.74	1.265	1.62	No	No	Yes
J-3792	710	71	693.88	69.39	1.612	2.27	No	No	Yes
J-3802	650	65	656.46	65.65	0.646	0.99	Yes	Yes	Yes
J-3817	580	58	732.56	73.26	15.256	26.30	No	No	No
J-3821	700	70	703.6	70.36	0.36	0.51	Yes	Yes	Yes
J-3827	400	40	507.59	50.76	10.759	26.90	No	No	No
J-3839	690	69	808.86	80.89	11.886	17.23	No	No	No
J-3851	520	52	509.83	50.98	1.017	1.96	No	Yes	Yes
J-3852	410	41	415.64	41.56	0.564	1.38	Yes	Yes	Yes
J-3872	820	82	728.46	72.85	9.154	11.16	No	No	No
J-3880	550	55	549.33	54.93	0.067	0.12	Yes	Yes	Yes
J-4046	730	73	923.26	92.33	19.326	26.47	No	No	No
J-2874	620	62	608.7	60.87	1.13	1.82	No	Yes	Yes
%age Compliance =							**32%**	**41%**	**55%**
Model Pressure Accuracy =						**10%**			

Discussion

Observed discrepancies between the model's "goodness-of-fit" value and the simulated fitness values (3909, 5163.67 and 5927.3) were relatively low considering the highly complex nature of the simulated water distribution network. The highly variable configuration of the network (and thus the selected field test sites for the different datasets) implied that the fitness values would not be absolutely equal. Values within 100% of each other suggested relatively consistent simulation-accuracy levels of the different locations within the network. However, a better indication of this consistency could be deduced from the actual model accuracies and compliance to the internationally proposed limits.

The average percentage error of the simulated flow parameters for the first post-calibration dataset was 11%, while that for the second was 17%. This represented a discrepancy of about 12% and 6% from the modelled flow accuracy. It could therefore be construed that the model's accuracy is comparatively greater in certain areas of the network. Consequently, the model's accuracy was established as inconsistent. Further research was thus proposed to analyse the spatial variability of accuracy levels (establish the presence of 'accuracy zones') and identify factors affecting any identified trends. This was beyond the scope of this analysis, which was limited to establishing the presence and extent of accuracy-consistency discrepancies. On that note, while margins of 6% and 12% between accuracy levels appear small, and hence tend to lend credence to the validity of the utilised model construction and calibration guidelines, never-the-less, the process results in locations of variable comparative accuracy within the simulated network.

In addition, upon consideration of the international calibration accuracy guidelines, both flow and pressure parameters were found to be incompliant for both datasets except the first dataset's 15%-maximum head-loss requirement. For the first post-calibration dataset, 50% of the pipes with discharge greater than 14.07 l/s were within the 5% acceptability limit, while 71% of the pipes with discharge less than 14.07 l/s were within the acceptability limit of 10% (*see Table 7 above*). Basing on this dataset, flow accuracies could almost be considered as viable in spite of the 100% compliance flow limit (*see Table 2*). It could also be noted that the overall accuracy recorded for this dataset was 11% which is relatively closer to the proposed 5 – 10% limit. This dataset was therefore found to have generally recorded greater levels of accuracy compared to the calibration dataset.

A similar observation could be made for the second post-calibration dataset, where percentage flow compliances were 20% and 47% (*see Table 9*), and overall accuracy was 17%. It was however noted that the second dataset appeared to be in greater agreement with the calibration accuracy levels than the first, possibly a result of test-locations biased towards 'low-accuracy' zones, or the variation of an external error source (*see section 4.3.1*). As suggested earlier, the effect of error sources on the model should form the basis of further study into this field. However, in general the recorded flow compliance values for the two datasets represented a considerable variation from the calibration accuracy values (0% and 18%), which appears to emphasise that the adopted model development process resulted in locations of variable accuracy within the simulated network.

Considering pressure accuracy levels, the limits of 85%, 95% and 100% for both datasets were not achieved except the first dataset's 15%-maximum head-loss requirement. However, the first dataset recorded high overall accuracy levels (1%), while the second dataset recorded an overall accuracy of 10% which was relatively low albeit fairly acceptable. On the whole therefore, the post-calibration datasets reinforce the notion that the model's pressure simulations could probably suffice for utility's requirements. However as earlier noted, based on the international accuracy guidelines, the model's pressure simulations would be incorrectly disqualified basing on the 85% and 95% limits (for both datasets) and the 100% limit for the second dataset. Streamlining of these guidelines as earlier suggested would therefore be appropriate.

The inconsistent nature of accuracy and compliance levels for both post-calibration datasets was found to be in agreement with those for flow. Similar deductions to those given earlier can therefore be made concerning the spatial consistency of the simulated network's accuracy and the effect of extraneous factors.

A global survey of all the test results (both calibration and post-calibration) reveals only 3 cases of gross discrepancy (greater than 50% error) out of over 120 test locations. This suggests that the accuracy levels of the developed model are generally agreeable and could be used satisfactorily for the practical application. However, for applications requiring high sensitivity (targeted in the internationally proposed guidelines), greater rigor would be required to establish and eliminate the sources of the recorded error.

Figure 19 below illustrates how each of the datasets compared with the internationally proposed flow and pressure calibration guidelines. As mentioned in the preceding discussions, only one of the cases was found to be compliant yet the simulated accuracies (particularly for pressure) were within acceptable limits for the purpose of the model.

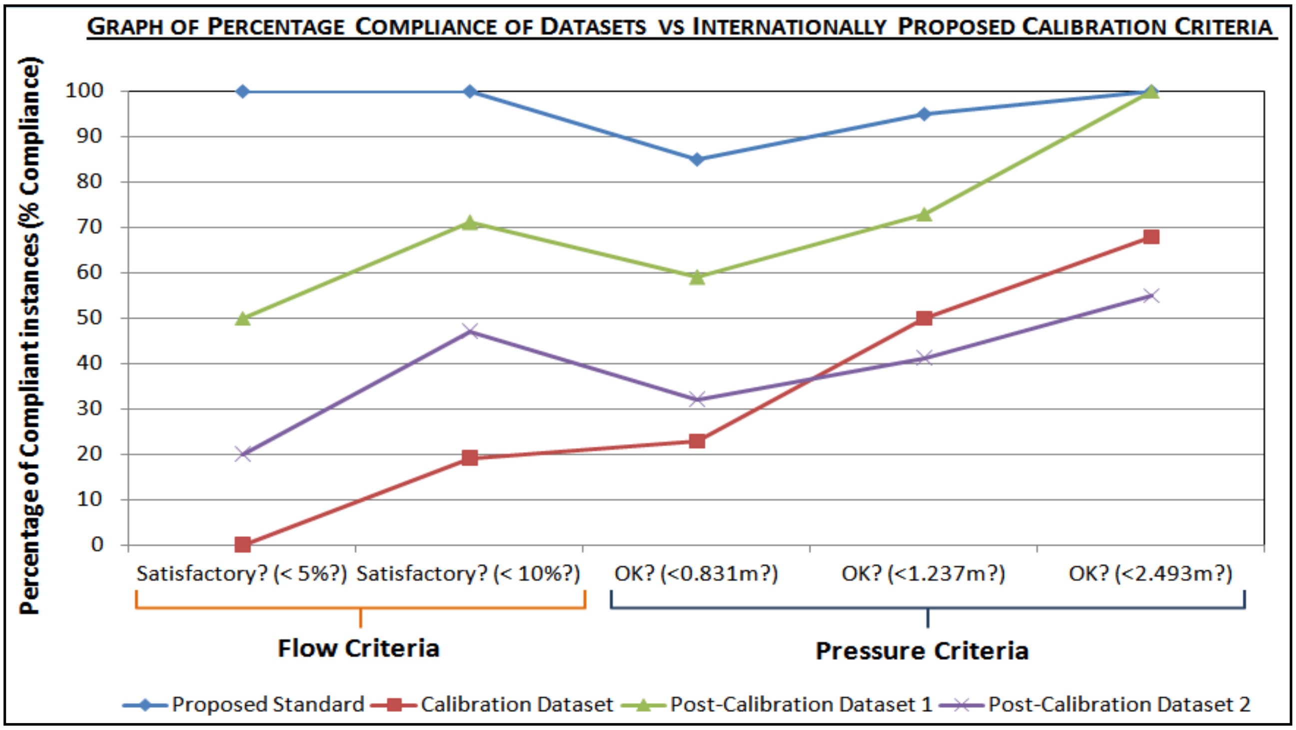

Figure 19: *Graph comparing compliance of the 3 datasets in relation to the proposed calibration guidelines*

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

Having documented and discussed the results of the research in the previous chapter, the pertinent conclusions and recommendations from the study are provided here below. The first section contains conclusions arising from each of the research sub-objectives, while the second section details the recommendations arrived at from the study as a whole.

5.1 CONCLUSIONS

The following conclusions were derived from the study.

1. THE STRATEGIC HS PERSPECTIVE

Whilst the utility had wide-ranging needs requiring a model with '*near-negligible'* skeletonisation, the resources available, given the utility's economic environment, couldn't support such an exercise. Nevertheless, the resulting modelling paradigm – '*low-skeletonisation, large-scale*' network simulation – provided a model of 605 pipes and 422 junctions, detail which was considered adequate for the validation exercise. A developing economic environment should not therefore hinder the construction of meaningful and high utility models.

2. MODEL CONSTRUCTION

The model was constructed based on methods proposed internationally. The data necessary for the study was successfully acquired (100% of pipe attribute data, node elevations to within 2 metres accuracy, and all relevant tank dimensions); as well as the software, and recommended test equipment and locations. It can therefore be inferred from the successful construction of such an extensive model; that internationally proposed methodologies do not pose any apparent insurmountable challenge to KW for the development of operational models on a local scale.

3. MODEL CALIBRATION

The model construction and calibration methodologies employed in the study resulted in variable model accuracy levels with error margins from 0% to over 60%, indicating simulated network accuracy of variable consistency, exceeding acceptable limits in some locations.. Therefore, using these internationally proposed guidelines; does not automatically eliminate the occurrence of error due to extraneous sources, which affect the quality of the resulting model.

4. POST-CALIBRATION MODEL ANALYSIS

As indicated in the previous chapter, out of over 120 test locations for both pressure and flow, only 3 cases of gross discrepancy were observed, yet the internationally proposed calibration limits were fulfilled in only 1 of the 6 test datasets. It can therefore be concluded that the existing international calibration-accuracy guidelines are mostly suitable for high-accuracy simulation (95%–100% model sensitivity) and erroneously discard valid simulation data when the objective lies within moderate accuracy.

However, the flow simulation calibration guidelines offered a consistent verdict in all the three cases, and therefore could be utilised as modelling standards subject to prevailing local conditions.

5.2 RECOMMENDATIONS

The following recommendations are found to be pertinent;

- Despite its accuracy and consistency limitations, the model can and should be employed for utility purposes requiring moderate accuracy. These include network master planning for large extensions, network subdivision design, and rural water system extensions (no fire protection), distribution system rehabilitation studies, flushing, and general operational problems (Walski *et al.*, 2003). Additionally, model calibration is a continuous process and should be done as frequently as is feasible to the utility to cater for changes in network configuration, consumption patterns, operational changes etc.

- The existing pressure guidelines should be adopted only for applications that dictate very high model accuracy levels (95% – 100%). Models developed for moderate and low accuracy levels shouldn't be subjected to them.

- Any standardised guidelines subsequently developed should provide for stratified accuracy levels to avoid the disqualification of valid data. Construction and calibration guidelines should be developed for different levels of accuracy depending on the desired application.

- For instance, the existing guidelines could be restricted to situations where only accuracies less than 5% are acceptable. Less stringent guidelines would then apply for acceptable accuracies between 5% - 10%, 10% - 15% and so on. Models for each of these accuracy bands and corresponding modelling paradigms should therefore be constructed and analysed accordingly to establish their requisite calibration criteria.

- Further research should be undertaken to establish the significance of the various sources of error on the ultimate accuracy of the model given the prevailing local considerations. Also, future studies could investigate why the model's pressure accuracy was better than flow accuracy.

- Finally, more study should also be done to analyse the possible existence of spatial trends in the variability between calibrated and simulated network's accuracy levels (to establish the presence of 'accuracy zones') and identify factors affecting any identified trends.

5.3 CONTRIBUTION TO SCIENCE

The technology and concepts applied in this research, particularly the development of a *large-scale low skeletonised* water distribution model; had never been studied under the conditions of the water distribution networks in Uganda and Kampala city in particular. This study has revealed the suitability of the proposed international model construction assumptions, best-practices, and data collection methodologies to the unique local conditions of the Kampala water distribution network, namely; poorly structured network configurations, inadequate flows resulting in partially full pipe-flows, and improperly designed network extensions. In this, the study has revealed that these concepts can be feasibly applied to the local water network conditions.

However, the research has also revealed that models calibrated using the Genetic Algorithm optimisation technique are not automatically immune to extraneous discrepancies. In addition, the achieved accuracy levels are variable across the network, exceeding 50% variation in some locations. It also revealed that the existing calibration-accuracy guidelines (AWWA, 1999; USEPA, 2005, Walski *et al.*, 2006) are mostly suitable for high-accuracy simulation and may erroneously discard valid simulations when the objective lies within moderate accuracy, which is common for utilities in the developing world with limited technological and financial resources.

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APPENDIX I – DRAWINGS

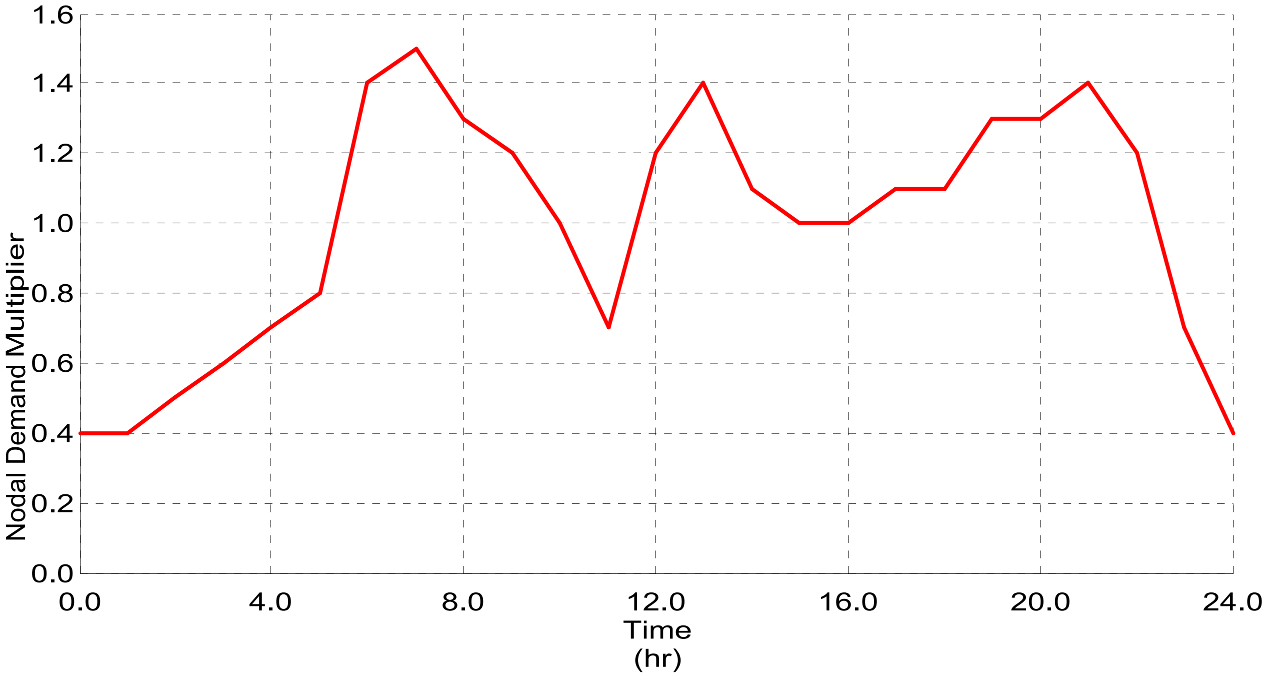


Figure A1-1: Diurnal Demand Curve – Naguru Supply Area

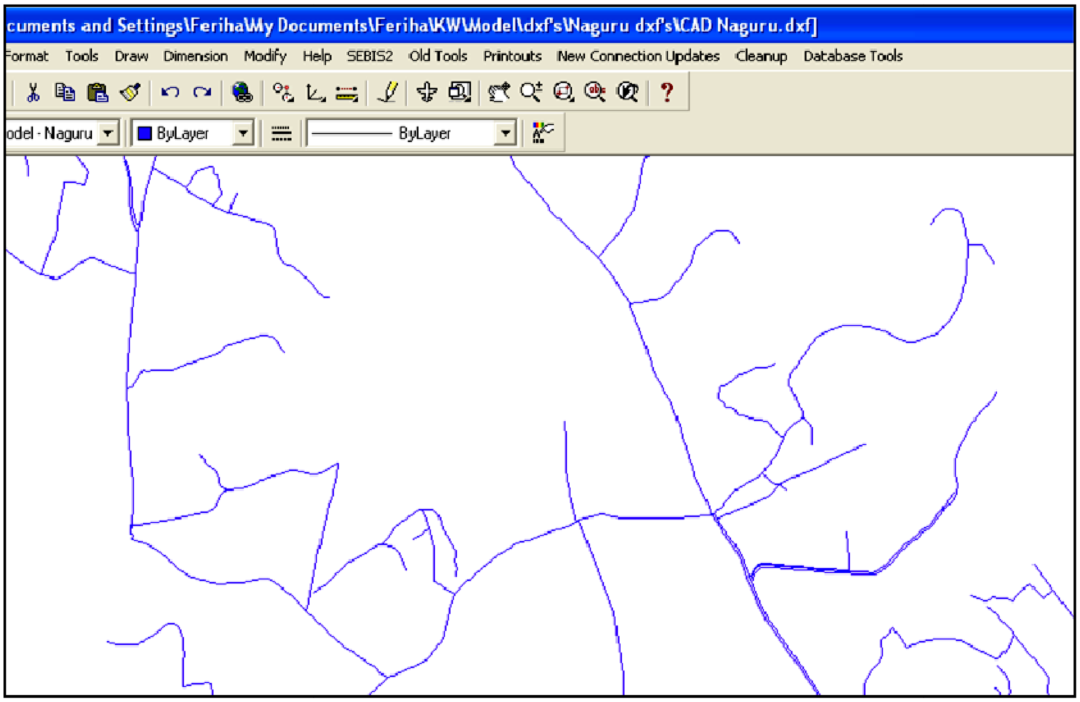
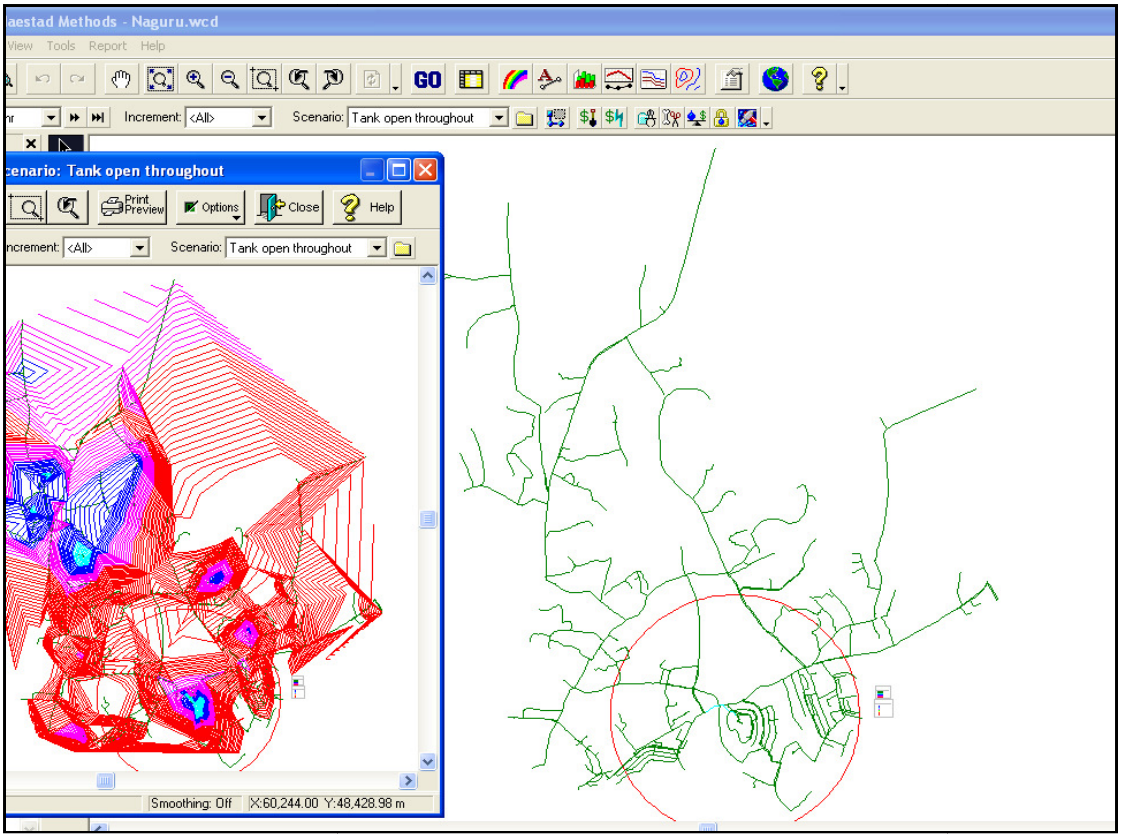


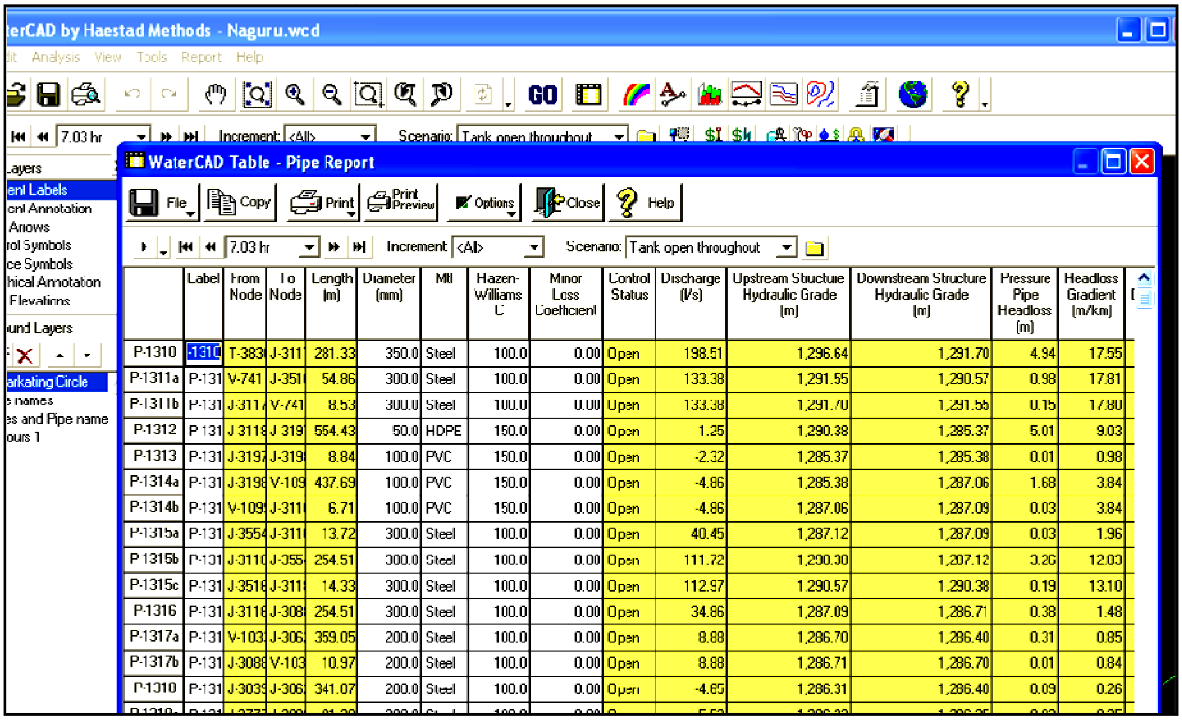
Figure A1-2: *CAD polylines of the Naguru water network set to be imported into WaterCAD*



Increment: <All>

Scenario: Tank open throughout

Figure A1-3: *Naguru Water Network imported into WaterCAD (Inset are test-simulation graphics)*



	Label	From Node	To Node	Length (m)	Diameter (mm)	Mtl	Hazen-Williams C	Minor Loss Coefficient	Control Status	Discharge (l/s)	Upstream Stucture Hydraulic Grade (m)	Downstream Structure Hydraulic Grade (m)	Pressure Pipe Headloss (m)	Headloss Gradient (m/km)
P-1310	-1310	T-383	J-311	281.33	350.0	Steel	100.0	0.00	Open	198.51	1,296.64	1,291.70	4.94	17.55
P-1311a	P-131	V-741	J-351	54.86	300.0	Steel	100.0	0.00	Open	133.38	1,291.55	1,290.57	0.98	17.81
P-1311b	P-131	J-311	V-741	8.53	300.0	Steel	100.0	0.00	Open	133.38	1,291.70	1,291.55	0.15	17.80
P-1312	P-131	J-311	J-319	554.43	50.0	HDPE	150.0	0.00	Open	1.25	1,290.38	1,285.37	5.01	9.03
P-1313	P-131	J-319	J-319	8.84	100.0	PVC	150.0	0.00	Open	-2.32	1,285.37	1,285.38	0.01	0.98
P-1314a	P-131	J-319	V-109	437.69	100.0	PVC	150.0	0.00	Open	-4.86	1,285.38	1,287.06	1.68	3.84
P-1314b	P-131	V-109	J-311	6.71	100.0	PVC	150.0	0.00	Open	-4.86	1,287.06	1,287.09	0.03	3.84
P-1315a	P-131	J-355	J-311	13.72	300.0	Steel	100.0	0.00	Open	40.45	1,287.12	1,287.09	0.03	1.96
P-1315b	P-131	J-311	J-355	254.51	300.0	Steel	100.0	0.00	Open	111.72	1,290.30	1,207.12	3.26	12.03
P-1315c	P-131	J-351	J-311	14.33	300.0	Steel	100.0	0.00	Open	112.97	1,290.57	1,290.38	0.19	13.10
P-1316	P-131	J-311	J-308	254.51	300.0	Steel	100.0	0.00	Open	34.86	1,287.09	1,286.71	0.38	1.48
P-1317a	P-131	V-103	J-306	359.05	200.0	Steel	100.0	0.00	Open	8.88	1,286.70	1,286.40	0.31	0.85
P-1317b	P-131	J-308	V-103	10.97	200.0	Steel	100.0	0.00	Open	8.88	1,286.71	1,286.70	0.01	0.84
P-1310	P-131	J-303	J-306	341.07	200.0	Steel	100.0	0.00	Open	-4.65	1,286.31	1,286.40	0.09	0.26

Figure A1-4: *Pipe attribute data imported from the GIS access database into the model*

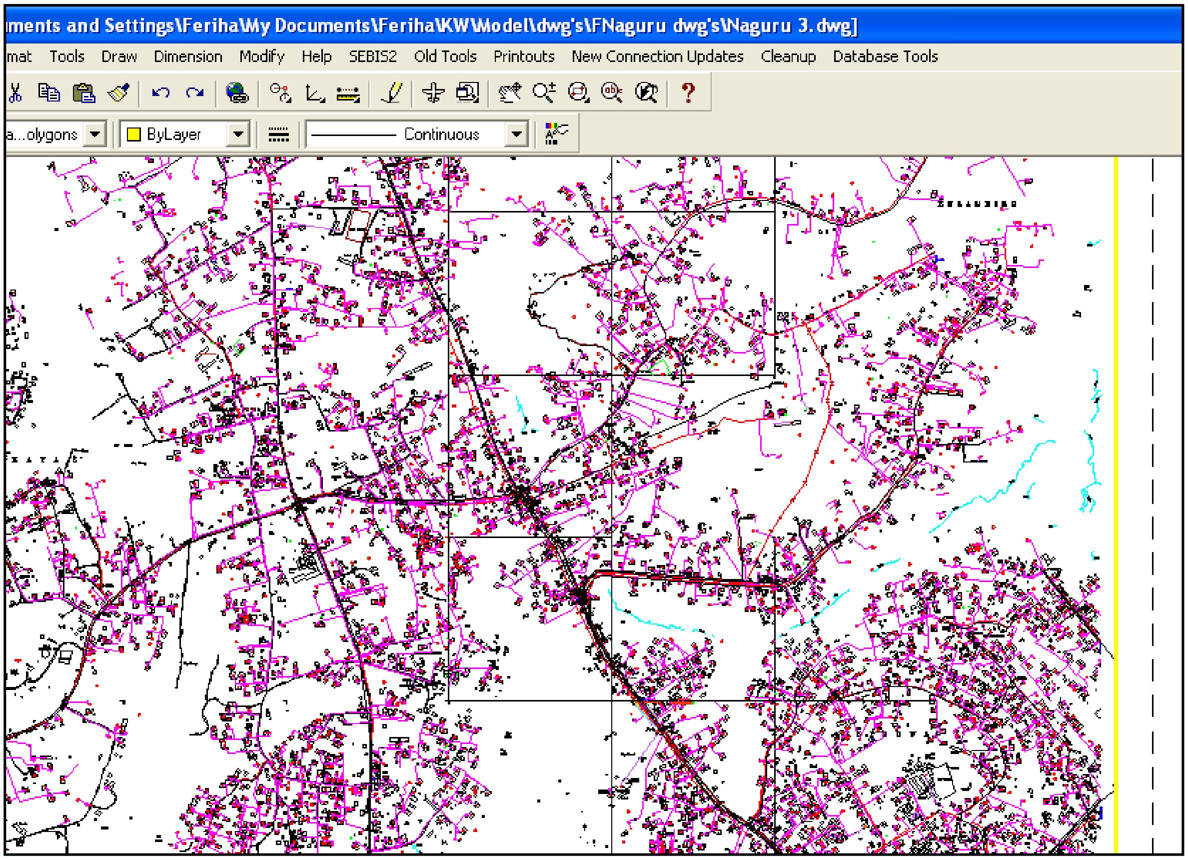


Figure A1-5: *Aggregated Customer Block Maps with Model Network in Background*

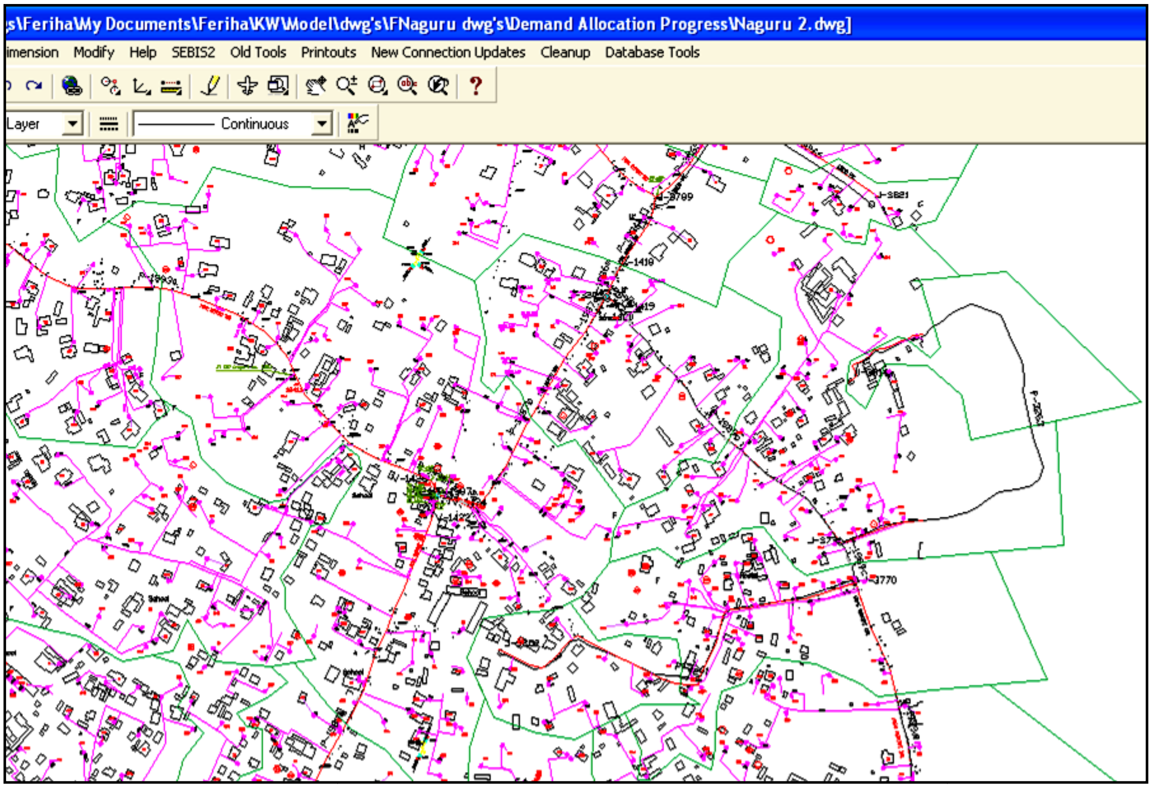


Figure A1-6: *Typical Customer Demand Polygons (green lines)*

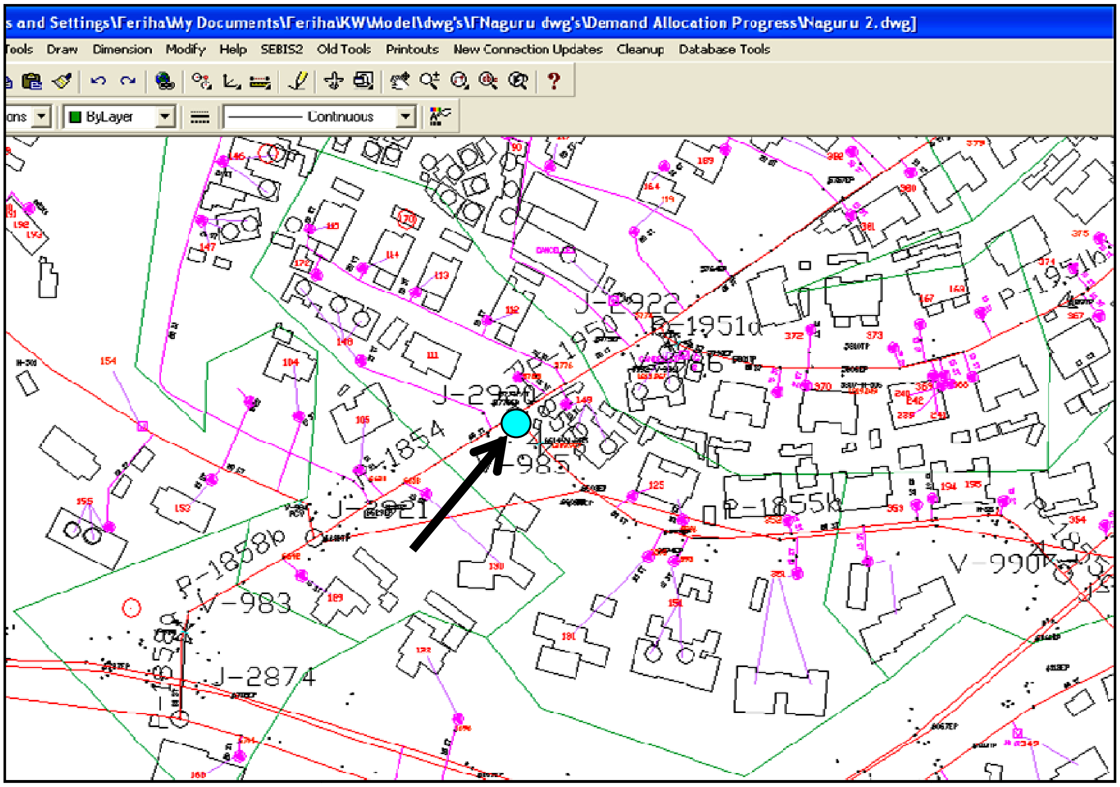


Figure A1-7: *Example of demand polygon lines (green) around a network junction*

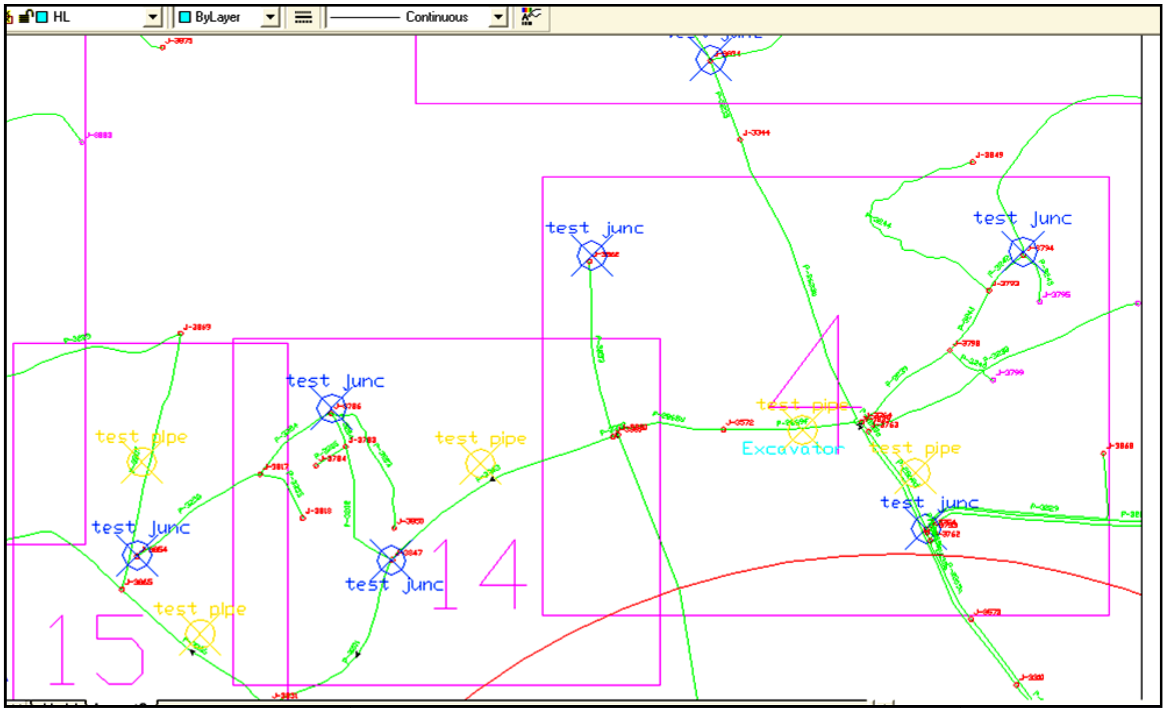
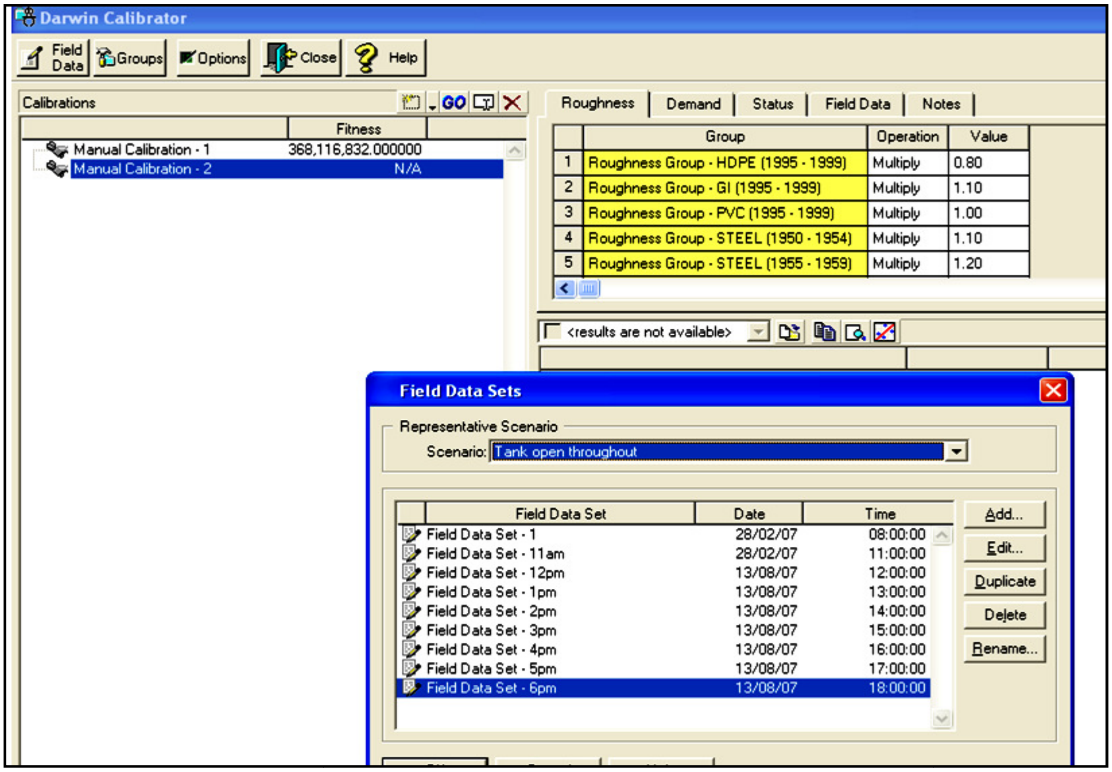


Figure A1-8: *Sampled calibration test locations indicated on the model network.*



Calibrations

	Fitness
Manual Calibration - 1	368,116,832.000000
Manual Calibration - 2	N/A

	Group	Operation	Value
1	Roughness Group - HDPE (1995 - 1999)	Multiply	0.80
2	Roughness Group - GI (1995 - 1999)	Multiply	1.10
3	Roughness Group - PVC (1995 - 1999)	Multiply	1.00
4	Roughness Group - STEEL (1950 - 1954)	Multiply	1.10
5	Roughness Group - STEEL (1955 - 1959)	Multiply	1.20

☐ <results are not available>

Representative Scenario

Scenario: Tank open throughout

Field Data Set	Date	Time
Field Data Set - 1	28/02/07	08:00:00
Field Data Set - 11am	28/02/07	11:00:00
Field Data Set - 12pm	13/08/07	12:00:00
Field Data Set - 1pm	13/08/07	13:00:00
Field Data Set - 2pm	13/08/07	14:00:00
Field Data Set - 3pm	13/08/07	15:00:00
Field Data Set - 4pm	13/08/07	16:00:00
Field Data Set - 5pm	13/08/07	17:00:00
Field Data Set - 6pm	13/08/07	18:00:00

Figure A1-9: *Field datasets loaded into the Darwin Calibrator.*

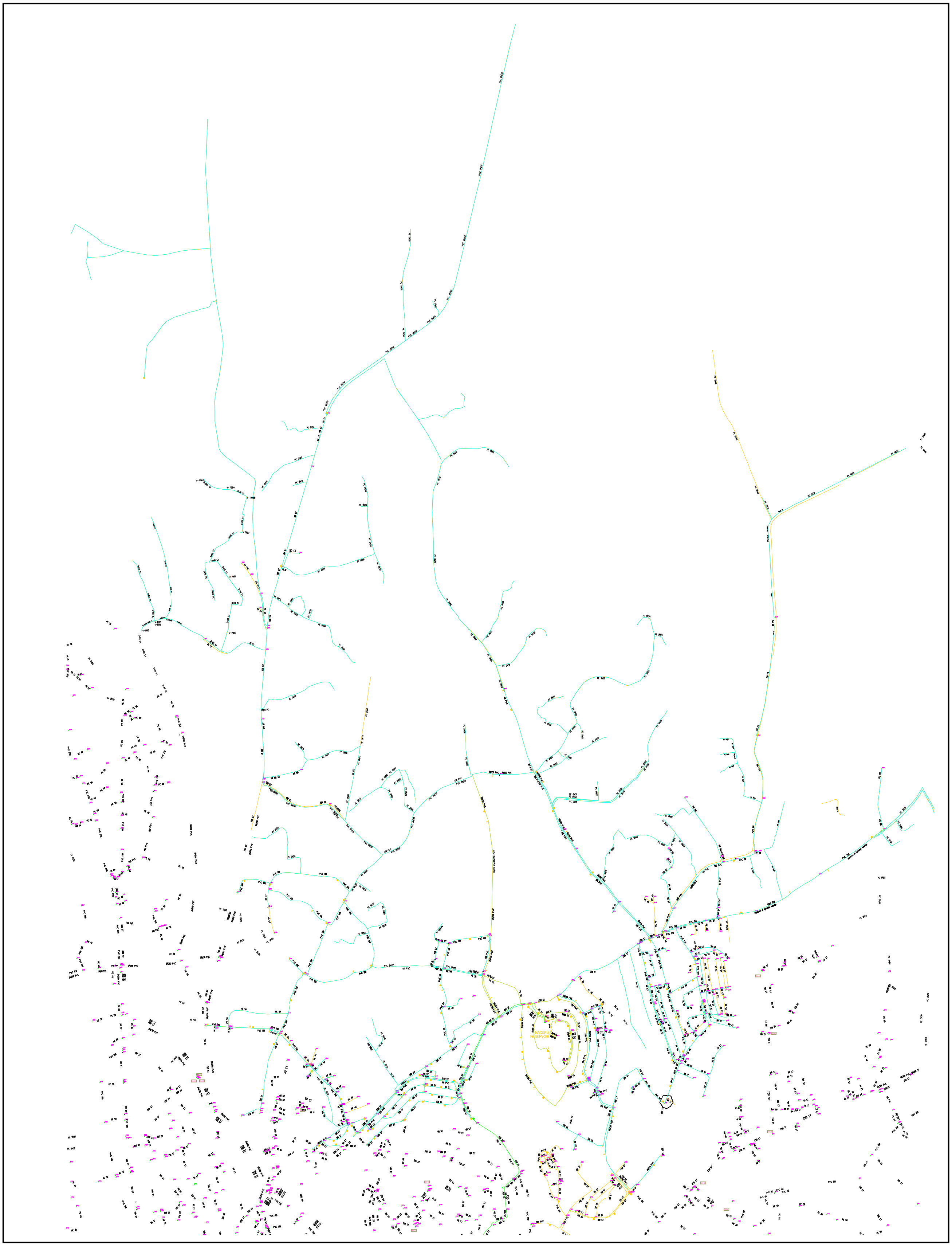


Figure A1-10: CAD Drawing of Naguru Supply Area with pipe material layer

Figure A1-11: Naguru Supply Area Model generated from imported DXF polylines

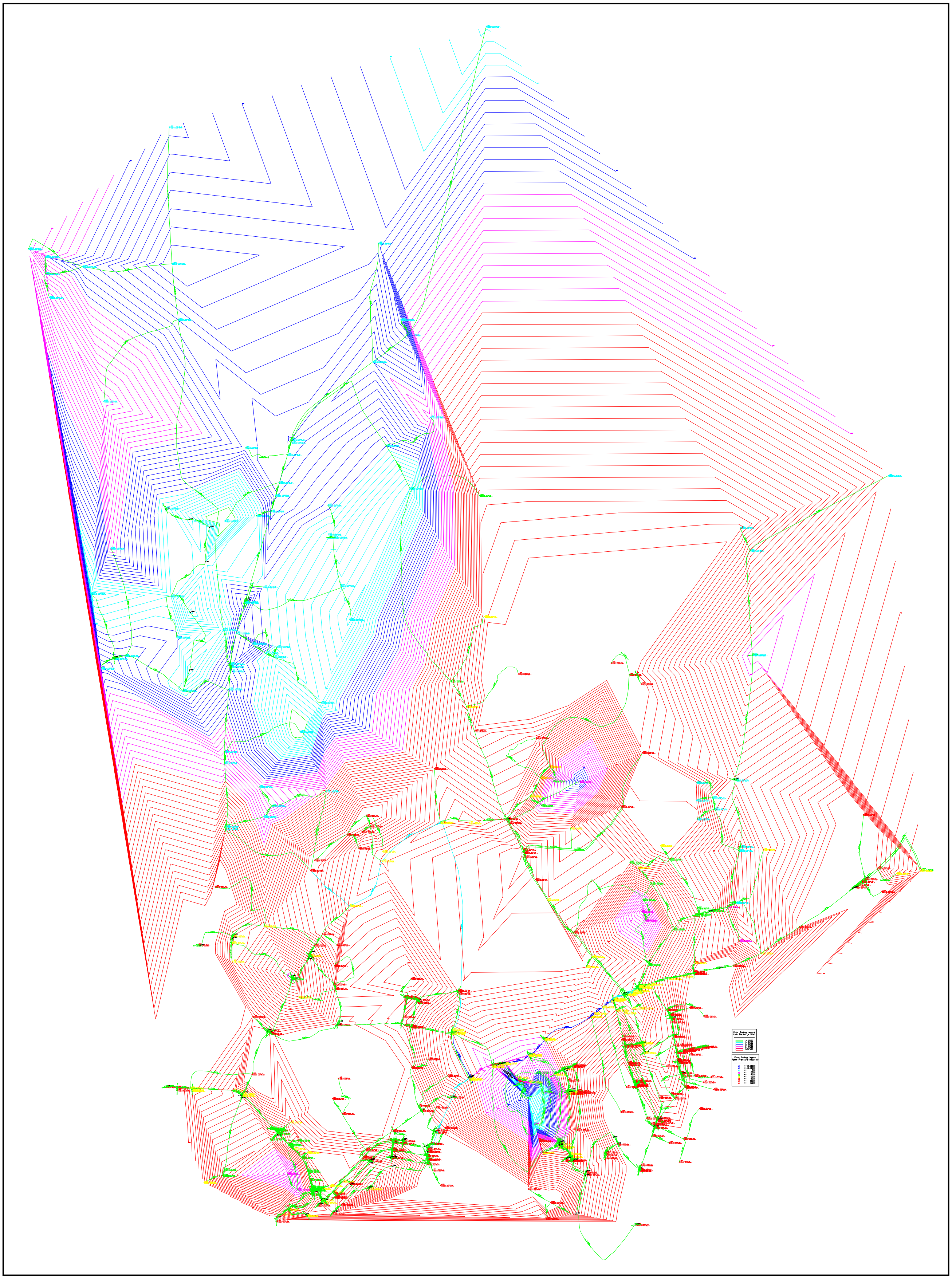
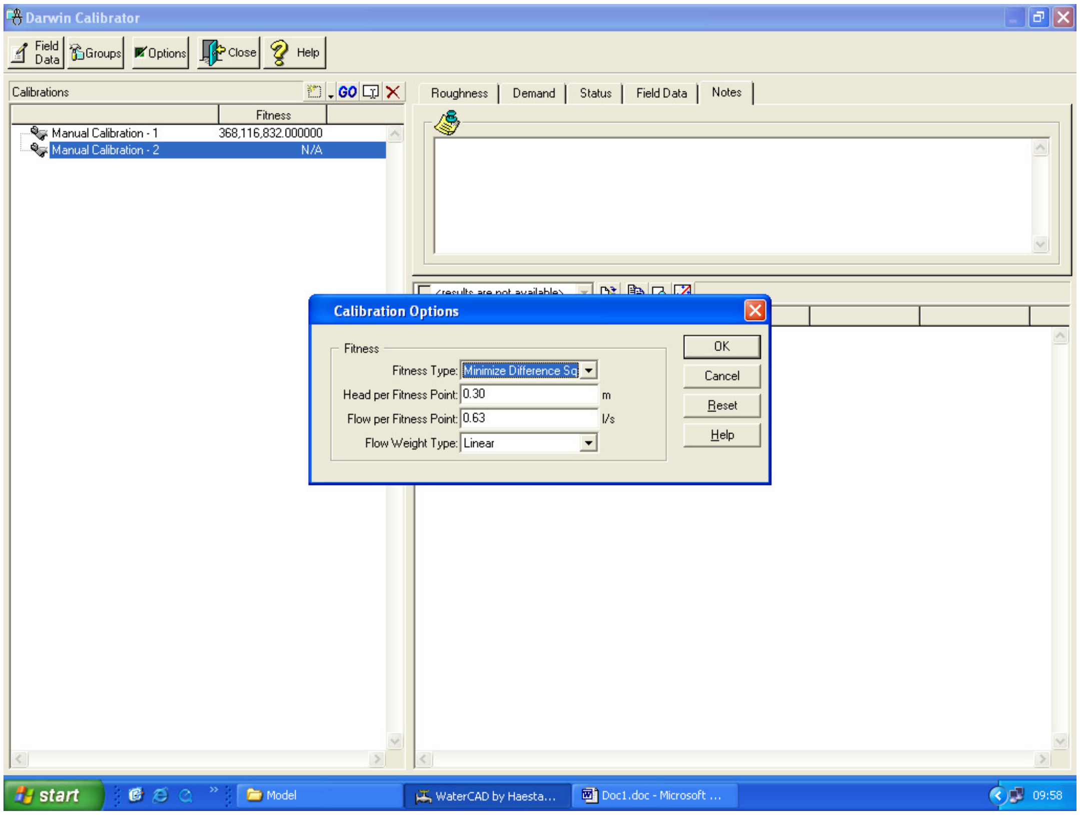


Figure A1-12: Pressure and Flow Contours indicating Model Simulated network behaviour



	Fitness
Manual Calibration - 1	368,116,832.000000
Manual Calibration - 2	N/A

Calibration Options

Fitness

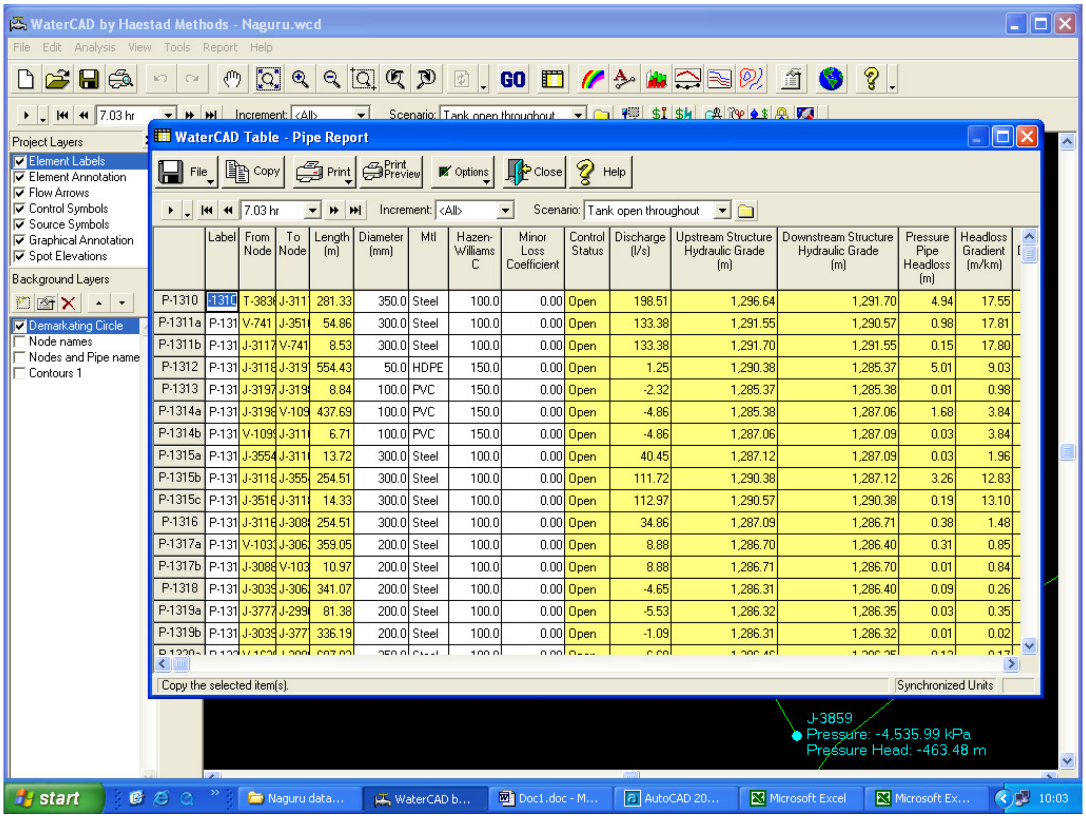
Fitness Type: Minimize Difference Sq

Head per Fitness Point: 0.30 m

Flow per Fitness Point: 0.63 l/s

Flow Weight Type: Linear

Figure A1-13: Model View – Selection of Calibration Optimisation Objective Function

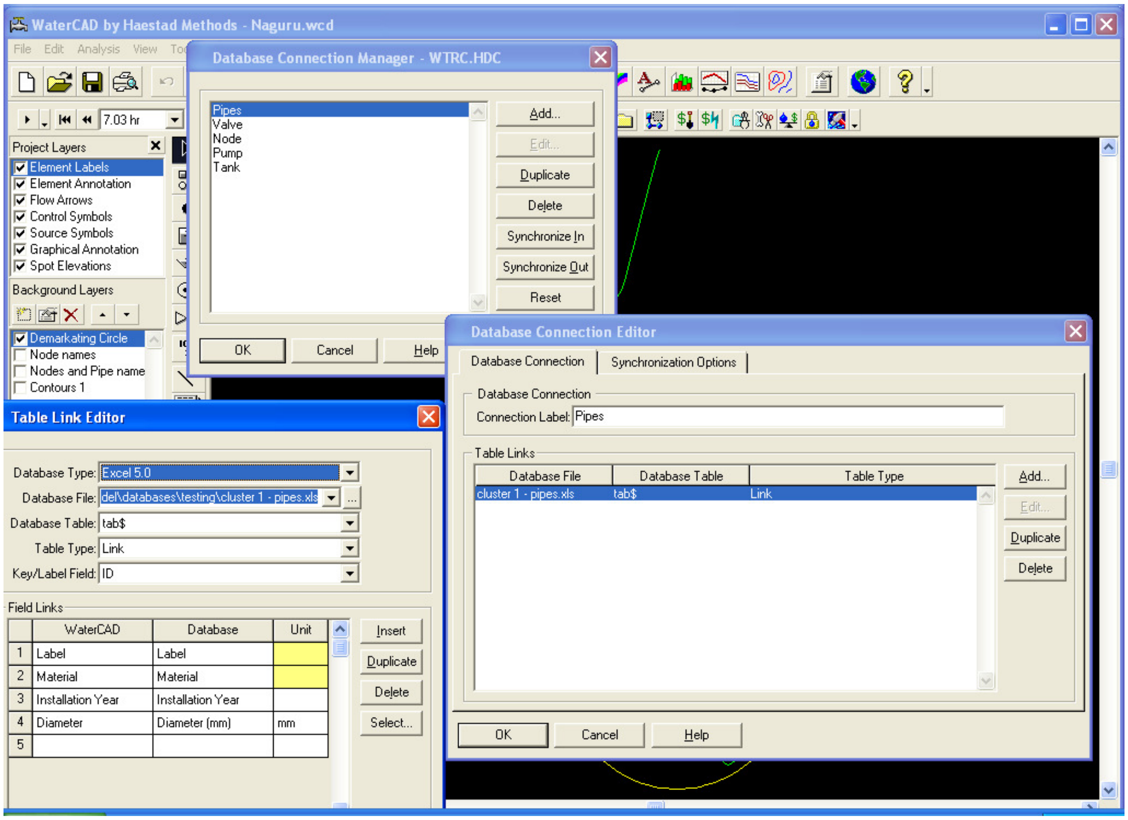


7.03 hr Increment: <All> Scenario: Tank open throughout

	Label	From Node	To Node	Length (m)	Diameter (mm)	Mtl	Hazen-Williams C	Minor Loss Coefficient	Control Status	Discharge (l/s)	Upstream Structure Hydraulic Grade (m)	Downstream Structure Hydraulic Grade (m)	Pressure Pipe Headloss (m)	Headloss Gradient (m/km)
P-1310	-1310	T-383	J-311	281.33	350.0	Steel	100.0	0.00	Open	198.51	1,296.64	1,291.70	4.94	17.55
P-1311a	P-131	V-741	J-351	54.86	300.0	Steel	100.0	0.00	Open	133.38	1,291.55	1,290.57	0.98	17.81
P-1311b	P-131	J-3117	V-741	8.53	300.0	Steel	100.0	0.00	Open	133.38	1,291.70	1,291.55	0.15	17.80
P-1312	P-131	J-311	J-319	554.43	50.0	HDPE	150.0	0.00	Open	1.25	1,290.38	1,285.37	5.01	9.03
P-1313	P-131	J-3197	J-319	8.84	100.0	PVC	150.0	0.00	Open	-2.32	1,285.37	1,285.38	0.01	0.98
P-1314a	P-131	J-319	V-109	437.69	100.0	PVC	150.0	0.00	Open	-4.86	1,285.38	1,287.06	1.68	3.84
P-1314b	P-131	V-109	J-311	6.71	100.0	PVC	150.0	0.00	Open	-4.86	1,287.06	1,287.09	0.03	3.84
P-1315a	P-131	J-3554	J-311	13.72	300.0	Steel	100.0	0.00	Open	40.45	1,287.12	1,287.09	0.03	1.96
P-1315b	P-131	J-311	J-355	254.51	300.0	Steel	100.0	0.00	Open	111.72	1,290.38	1,287.12	3.26	12.83
P-1315c	P-131	J-351	J-311	14.33	300.0	Steel	100.0	0.00	Open	112.97	1,290.57	1,290.38	0.19	13.10
P-1316	P-131	J-311	J-308	254.51	300.0	Steel	100.0	0.00	Open	34.86	1,287.09	1,286.71	0.38	1.48
P-1317a	P-131	V-103	J-306	359.05	200.0	Steel	100.0	0.00	Open	8.88	1,286.70	1,286.40	0.31	0.85
P-1317b	P-131	J-3088	V-103	10.97	200.0	Steel	100.0	0.00	Open	8.88	1,286.71	1,286.70	0.01	0.84
P-1318	P-131	J-303	J-306	341.07	200.0	Steel	100.0	0.00	Open	-4.65	1,286.31	1,286.40	0.09	0.26
P-1319a	P-131	J-3777	J-299	81.38	200.0	Steel	100.0	0.00	Open	-5.53	1,286.32	1,286.35	0.03	0.35
P-1319b	P-131	J-303	J-377	336.19	200.0	Steel	100.0	0.00	Open	-1.09	1,286.31	1,286.32	0.01	0.02

J-3859
Pressure: -4,535.99 kPa
Pressure Head: -463.48 m

Figure A1-14: Model View – Network Pipe Attribute Data



Project Layers
☑ Element Labels
☑ Element Annotation
☑ Flow Arrows
☑ Control Symbols
☑ Source Symbols
☑ Graphical Annotation
☑ Spot Elevations

Background Layers
☑ Demarkating Circle
☐ Node names
☐ Nodes and Pipe name
☐ Contours 1

Database Connection Manager:
Pipes
Valve
Node
Pump
Tank

Table Link Editor:
Database Type: Excel 5.0
Database File: del\databases\testing\cluster 1 - pipes.xls
Database Table: tab$
Table Type: Link
Key/Label Field: ID

Field Links

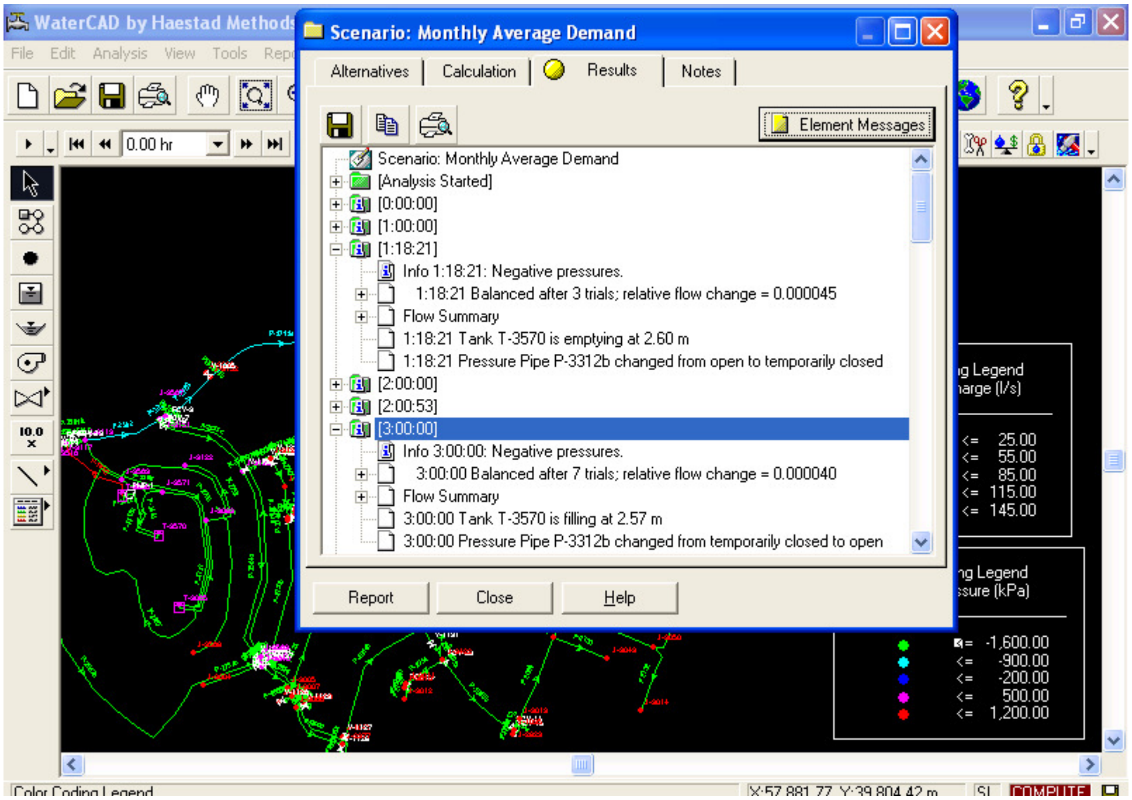
	WaterCAD	Database	Unit
1	Label	Label	
2	Material	Material	
3	Installation Year	Installation Year	
4	Diameter	Diameter (mm)	mm
5			

Database Connection Editor:
Connection Label: Pipes

Table Links

Database File	Database Table	Table Type
cluster 1 - pipes.xls	tab$	Link

Figure A1-15: Model View – External Data-source Connectivity



Scenario: Monthly Average Demand
[Analysis Started]
[0:00:00]
[1:00:00]
[1:18:21]
Info 1:18:21: Negative pressures.
1:18:21 Balanced after 3 trials; relative flow change = 0.000045
Flow Summary
1:18:21 Tank T-3570 is emptying at 2.60 m
1:18:21 Pressure Pipe P-3312b changed from open to temporarily closed
[2:00:00]
[2:00:53]
[3:00:00]
Info 3:00:00: Negative pressures.
3:00:00 Balanced after 7 trials; relative flow change = 0.000040
Flow Summary
3:00:00 Tank T-3570 is filling at 2.57 m
3:00:00 Pressure Pipe P-3312b changed from temporarily closed to open

ng Legend
harge (l/s)
<= 25.00
<= 55.00
<= 85.00
<= 115.00
<= 145.00

ng Legend
ssure (kPa)
<= -1,600.00
<= -900.00
<= -200.00
<= 500.00
<= 1,200.00

Figure A1-16: Model View – Base Scenario Hydraulic Simulation Results

APPENDIX II – RESULTS TABLES

Table A2-1: Excerpt of the Node Attribute Data – Coordinates, Elevations, and Demands

Label	X (m)	Y (m)	Elev. (m)	Base Flow (l/s)	HGL (m)	P (kPa)
J-1035	57,113.12	38,004.32	1,185.00	0.27	1,272.74	858.69
J-1939	57,674.96	39,755.90	1,189.00	0.08	1,270.93	801.88
J-2829	57,109.57	37,994.05	1,186.00	0	1,272.74	848.9
J-2849	53,752.34	37,684.53	1,211.00	0	1,283.26	707.22
J-2874	53,322.17	37,540.92	1,185.00	0.05	1,247.20	608.7
J-2920	53,438.53	37,646.39	1,211.00	0.19	1,247.20	354.29
J-2921	53,368.91	37,603.69	1,196.00	0.13	1,247.20	501.05
J-2922	53,489.28	37,676.75	1,217.00	0.59	1,247.23	295.88
J-2923	53,629.15	37,591.22	1,209.00	0.26	1,247.18	373.64
J-2925	53,814.48	37,723.57	1,214.00	0.27	1,256.96	420.48
J-2926	53,791.25	37,729.69	1,214.00	0.03	1,254.91	400.37
J-2927	53,907.62	37,613.38	1,215.00	0.06	1,280.73	643.27
J-2928	53,926.68	37,753.10	1,216.00	0	1,273.96	567.24
J-2929	53,994.37	37,691.23	1,223.00	0.84	1,280.73	564.98
J-2936	56,182.71	37,708.69	1,183.00	0.99	1,282.74	976.15
J-2937	56,133.35	37,565.75	1,206.00	0.19	1,282.64	750.04
J-2946	52,559.56	37,888.16	1,197.00	0.1	1,237.95	400.79
J-2947	52,763.64	37,949.88	1,221.00	0	1,237.95	165.91
J-2948	52,773.54	38,000.00	1,223.00	2.98	1,237.95	146.34
J-2958	53,430.34	37,964.77	1,247.00	0.03	1,244.81	-21.44
J-2960	53,666.33	37,913.41	1,216.00	0.49	1,244.84	282.25
J-2961	53,876.15	37,860.01	1,207.00	0.2	1,249.57	416.67
J-2962	53,691.80	37,819.54	1,218.00	0.08	1,246.50	278.91
J-2963	53,683.84	37,846.70	1,218.00	0.03	1,245.76	271.65
J-2964	53,707.61	37,805.60	1,217.00	0.56	1,247.63	299.82
J-2965	53,698.25	37,802.06	1,218.00	0.06	1,247.25	286.26
J-2966	53,745.03	37,818.66	1,213.00	0.58	1,249.58	357.98
J-2967	53,686.07	37,837.77	1,218.00	0	1,245.88	272.84
J-2968	53,904.97	37,800.75	1,212.00	0.07	1,260.06	470.36
J-2969	53,938.35	37,763.60	1,216.00	0.14	1,273.96	567.24
J-2970	54,007.22	37,898.56	1,212.00	0.54	1,263.77	506.66
J-2971	54,082.72	37,877.76	1,216.00	0.6	1,273.96	567.26
J-2972	54,294.73	37,842.68	1,232.00	0.69	1,280.77	477.33
J-2974	54,945.93	37,998.05	1,189.00	0	1,283.33	923.24
J-2976	55,946.66	37,829.38	1,192.00	0.84	1,282.65	887.2
J-2977	56,549.60	37,961.05	1,219.00	2.98	1,283.89	635.07
J-2988	53,643.88	37,987.47	1,215.00	0.09	1,243.91	282.94
J-2989	53,640.90	37,997.22	1,215.00	1.18	1,243.79	281.78
J-2990	53,640.77	38,155.08	1,206.00	1.1	1,241.96	351.92
J-2991	53,579.98	38,109.18	1,215.00	0.21	1,242.63	270.39

Table A2-2: Excerpt of the Pipe Attribute Data

Label	Length (m)	Diam (mm)	Mtl	Hazen-Williams C	Inst Yr	DG (l/s)	Head-loss (m)	Headloss Gradient (m/km)
P-1310	281.33	350	Steel	140	1998	191.33	0.46	1.64
P-1311a	54.86	300	Steel	140	1977	129.48	0.09	1.69
P-1311b	8.53	300	Steel	140	1977	129.48	0.01	1.69
P-1312	554.43	50	HDPE	135	1996	1.13	5.05	9.11
P-1313	8.84	100	PVC	150	1998	-2.36	0.01	1.01
P-1314a	437.69	100	PVC	150	1998	-5.15	1.87	4.28
P-1314b	6.71	100	PVC	150	1998	-5.15	0.03	4.26
P-1315a	13.72	300	Steel	140	1977	40.64	0.03	1.97
P-1315b	254.51	300	Steel	140	1977	108.85	0.31	1.22
P-1315c	14.33	300	Steel	140	1977	109.98	0.02	1.25
P-1316	254.51	300	Steel	140	1977	34.59	0.37	1.46
P-1317a	359.05	200	Steel	140	1977	9.03	0.31	0.88
P-1317b	10.97	200	Steel	140	1977	9.03	0.01	0.87
P-1318	341.07	200	Steel	140	1977	-4.35	0.08	0.23
P-1319a	81.38	200	Steel	140	1977	-5.55	0.03	0.36
P-1319b	336.19	200	Steel	140	1977	-0.98	0.00	0.01
P-1320a	687.02	250	Steel	93	1962	6.36	0.12	0.18
P-1320b	47.24	250	Steel	93	1962	6.36	0.01	0.18
P-1321	27.74	250	Steel	140	1998	8.46	0.01	0.26
P-1322	69.19	250	Steel	140	1998	16.84	0.06	0.94
P-1323a	7.92	100	Steel	140	1998	-16.75	0.06	8.05
P-1323b	7.01	100	Steel	140	1998	-16.75	0.06	8.05
P-1324	39.62	100	Steel	92	1958	-11.41	0.18	4.62
P-1325a	268.83	100	PVC	150	1998	-6.64	1.84	6.84
P-1325b	23.77	100	PVC	150	1998	-6.64	0.16	6.84
P-1326	26.21	80	Steel	92	1958	-4.34	0.06	2.28
P-1327a	27.74	80	Steel	92	1958	-4.47	0.07	2.42
P-1327b	139.6	80	Steel	92	1958	-4.47	0.34	2.42
P-1327c	11.89	80	Steel	92	1958	-4.47	0.03	2.42
P-1328a	145.69	80	Steel	92	1958	0	0.00	0.00
P-1328b	13.41	80	Steel	92	1958	0	0.00	0.00
P-1329	97.84	100	PVC	150	1998	-10.72	0.16	1.66
P-1330a	54.56	80	Steel	92	1958	-1.32	0.14	2.52
P-1330b	7.92	80	Steel	92	1958	-1.32	0.02	2.52
P-1331a	11.28	80	Steel	92	1958	3.2	0.01	1.30
P-1331b	239.57	80	Steel	92	1958	3.2	0.31	1.30
P-1331c	13.72	80	Steel	92	1958	3.2	0.02	1.30
P-1332a	277.37	100	Steel	92	1958	-2.6	0.83	2.99
P-1332b	18.29	100	Steel	92	1958	-2.6	0.05	2.99
P-1333	186.23	100	Steel	92	1958	0.14	0.00	0.01
P-1334	37.49	100	Steel	92	1958	0	0.00	0.00
P-1335a	10.36	100	PVC	150	1998	-13.64	0.03	2.60

Table A2-3 a, b, c: Diurnal Demand Curve

Demand Pattern: Pattern – 1

Pattern Summary

Pattern	Pattern - 1	**Format**	Continuous
Start Time	00:00:00	**Starting Multiplier**	0.40
Duration	24.00 hr		

Time from Start (hr)	1	2	3	4	5	6	7	8	9	10	11	12
Multiplier	0.4	0.5	0.6	0.7	0.8	1.4	1.5	1.3	1.2	1	0.7	1.2

Time from Start (hr)	13	14	15	16	17	18	19	20	21	22	23	24
Multiplier	1.4	1.1	1	1	1.1	1.1	1.3	1.3	1.4	1.2	0.7	0.4

Table A2-4: Pipe Network Sampling Frame

Pipe ID	Discharge (Absolute Value) (l/s)
P-3302	30.7
P-3303	29.91
P-3201	29.19
P-3206	28.91
P-1998	25.47
P-1999b	24.42
P-3304	23.76
P-3305	23.48
P-1999a	23.15
P-2639c	19.03
P-2000a	18.97
P-2639b	18.63
P-2000b	17.6
P-2001	17.54
P-2002a	16.85
P-2640a	16.54
P-2640c	16.54
P-2640b	16.54
P-2868d	15.57
P-2869f	15.27
P-2002b	15.25
P-2641a	15.2
P-1335a	14.51
P-2641b	14.42
P-1945a	14.11
P-1945b	14.11
P-1946b	14.08
P-1946c	14.08
P-1946a	14.08
P-1990	13.65
P-2643a	13.44
P-1947	13.27
P-2869e	12.86
P-1992b	12.4
P-1992a	12.4
P-2002c	12.18
P-2869d	11.9
P-1948	11.72
P-2869c	11.7
P-1952	11.49
P-2003a	11.46
P-2003b	11.46
P-1989h	11.36
P-2003c	11.25
P-2004a	11.14
P-2775d	11.11
P-2774a	10.82
P-2643b	10.74
P-2004b	10.59
P-1972a	10.39
P-1972b	10.39
P-1953a	10.1
P-1953b	10.1
P-1954	10.1
P-1956	10.08
P-2004c	10.07
P-2774b	10.04
P-2004d	9.65
P-3285	9.62
P-1970	9.57
P-1989a	9.35
P-1989b	9.35
P-1958	9.34
P-1960	9.25
P-2776a	9.13
P-2776b	9.13
P-2776c	9.13
P-3287	8.32
P-2776d	8.29
P-2776e	8.26
P-1961	8.08
P-1964a	7.27
P-2644	6.85
P-1963	6.77
P-1969b	6.67
P-1969a	6.67
P-1964b	6.29
P-3289	5.39
P-2776g	5.34
P-2776f	5.34
P-1987b	5.26
P-1987c	5.26
P-1987a	5.26
P-3207	5.09
P-2876a	4.92
P-2876b	4.92

Table A2-5: Network Junction Sampling Frame

ID	Min. HGL (m)	Min. P (kPa)
J-3765	1263.98	939.36
J-4046	1263.86	889.21
J-3327	1263.83	849.8
J-3839	1263.47	777.74
J-3282	1266.83	761.75
J-3874	1254.48	758.25
J-3786	1263.3	756.51
J-3891	1269.77	751.3
J-3854	1263.25	746.29
J-3289	1254.19	745.68
J-3766	1263.93	733.35
J-3306	1265.15	725.73
J-3828	1252.39	718.23
J-3581	1257	714.45
J-2849	1283.56	710.12
J-3817	1263.25	697.36
J-3753	1273.76	692.51
J-3872	1236.96	684.7
J-3754	1273.76	682.77
J-3894	1261.05	666.01
J-3783	1263.3	658.7
J-3784	1263.3	658.69
J-3821	1255.15	657.21
J-3792	1255.16	647.48
J-3113	1243.12	637.33
J-3802	1252.44	630.7
J-3814	1260.17	628.04
J-3803	1252.42	620.64
J-3826	1254.68	613.45
J-3189	1252.46	611.27
J-3192	1253.22	608.93
J-3077	1238.03	607.06
J-3865	1247.47	591.8
J-3771	1260.3	590.2
J-3763	1273.98	587.05
J-2874	1244.51	582.46
J-3190	1252.44	581.7
J-3849	1260.01	577.51
J-3764	1274.01	577.51
J-3862	1273.7	574.45
J-3861	1274.31	541.35
J-3818	1263.25	540.77
J-3080	1238.05	538.76
J-3082	1238.05	538.74
J-3880	1274.55	533.88
J-3789	1255.38	532.23
J-3344	1245.68	525.38
J-3868	1273.66	525.12
J-3886	1266.03	518.95
J-3877	1263.93	518.03
J-3827	1254.64	505.41
J-3841	1266.1	500.07
J-3572	1274.43	493.56
J-3850	1263.27	482.21
J-3293	1254.19	481.45
J-3292	1254.18	481.3
J-2921	1244.51	474.81
J-3847	1263.34	473.05
J-3798	1264.36	463.51
J-3851	1254.99	459.88
J-3272	1250.68	447.04
J-3273	1255.65	446.77
J-3848	1254.48	445.07
J-3078	1238.1	441.41
J-3079	1238.11	421.91
J-3081	1238.11	421.91
J-3879	1232.1	412
J-2925	1255.22	403.39
J-2961	1247.06	392.02
J-2926	1252.95	381.19
J-3852	1260.93	380.98
J-2946	1235.31	374.89
J-3793	1260.05	372.36
J-3084	1240.02	372.12
J-3794	1257.56	367.61
J-3834	1237.38	365.81
J-3061	1236.34	365.48
J-3083	1238.52	347.67
J-2923	1244.5	347.4
J-3085	1237.68	339.42
J-2966	1247.06	333.36
J-3823	1237.01	332.88
J-2920	1244.52	328.05
J-2990	1239.12	324.15
J-3032	1238.88	321.76
J-3027	1238.84	311.59

Table A2-6: Excerpt of the Pipe Reconnaissance Survey Results

ULTRASONIC FLOW TESTING POINTS (Datasets 1, 2 and 3)

ID	**ID**	**Print out No:**	**General Location**	**Exact location**	**Excavation?**
P-2774b	P-2774b	#1	Naalya road	4m from air valve 186	Manual
P-1992a	P-1992a	#10	Kyebando road,off Mawanda road	Little Apostles Nursery	Manual
P-1964a	P-1964a	#10	Mawanda road	Road after road near AV82	Excavator
P-1969a	P-1969a	#10	Mawanda road	4m from air valve 081	Excavator
P-1989h	P-1989h	#11	Kyebando Ring Road	Use P-1989g instead, 5m from 2 valves	Manual
P-1989d	P-1989d	#13		Opposite Bushenyi Diary	Manual
P-1987b	P-1987b	#13		Cream Hill day, 4m from Hydrant 778, at Road junctn	Manual
P-3303	P-3303	#14	Kikaya (road)	Opposite house in swamp area	Manual
P-3206	P-3206	#15	Kikaya road	Near AV, 3m from FCV, adjcent to the Main gate of Bahai at Hill Crest. Acc 12/20/120	Manual
P-3207	P-3207	#15	Kikaya-Kanyanya Road	Near 10/20/56/ after pipe road crossing, DN50	Non required
P-2876a	P-2876a	#2	Shelter road	4m from valve 1645	Manual
P-2639b	P-2639b	#3	Old Kira Road	Christ Center Church	Manual
P-2644	P-2644	#3	Old Kira Road		Manual
P-2869f	P-2869f	#4	Kulambiro Road	DN 200	Excavator
P-2869d	P-2869d	#4	Kisaasi Road	before the valves,DN200	Manual
P-3237	P-3237	#5	Kyanja	4m from 5/22/21,DN 50	Manual
P-3224	P-3224	#6	Najera	4m from Air valve	Manual
P-2003b	P-2003b	#7	Komamboga,Gyza road	Opposite MUK staff quarters	Excavator
P-2004b	P-2004b	#7	Komamboga	Kla-Gyza road, DN 80 steel	Excavator
P-3287	P-3287	#7	Luteete, Kampala Gyza road	Near Parambot traders, DN150	Manual
P-1999b	P-1999b	#8	Mpererwe, Gyza road		Excavator
P-2000a	P-2000a	#8	Mpererwe, Gyza road		Excavator
P-1946c	P-1946c	#9	Kira Road, Kayunga Road	4m along P-1946b	Excavator
P-1956	P-1956	#9	Mawanda road	DN 100	Excavator
P-1961	P-1961	#9	Mawanda road	Infront of Drive in washing bay,DN100	Excavator

Table A2-7: Excerpt of the Junction Reconnaissance Survey Results

PRESSURE TESTING POINTS

ID	ID	Print out No:	General Location	Exact location	Excavation?	Extra equip
J-3841	J-3841	#1	Naalya road	At air valve 186	None required	Spanners
J-3113	J-3113	#10	Kyebando road,off Mawanda road	Little Apostles Nursery,DN 100	Manual	Drill, Saddle, Spanners
J-3080	J-3080	#10	Mawanda Road, near Kalerwe	Near valve RAV, on DN100	Excavator or Manual team of 3	Drill, Saddle, Spanners
J-3775	J-3775	#10	Mawanda Road	At AV 082, opposite Kwik sale Supermarket	Manual	Spanners
J-3192	J-3192	#11	Kyebando Ring Road	5m Along P-1989g	Manual	Drill, Saddle, Spanners
J-3190	J-3190	#11	Kyebando Ring Road	At AV 138, Needs allen key	None required	Spanners
J-3289	J-3289	#12	Gayaza road	Erisa road BodaBoda stage, 4m from T pipe junctn, Valve-1413	Excavator	Drill, Saddle, Spanners
J-3293	J-3293	#12	Kyebando Ring Road	Use H-776 at Junction,Secret Inn Poster	None required	Spanners
J-3272	J-3272	#12	Kyebando Ring Road	DN 50	Manual	Drill, Saddle, Spanners
J-3770	J-3770	#13		Test along P-1989d	Manual	Drill, Saddle, Spanners
J-3247	J-3247	#13		Use H-780,PVC 100	None required	Spanners
J-3786	J-3786	#14	Kikaya	20m from Lover's Guest house, DN80, Acc 10/21/26, at road junc	Manual	Drill, Saddle, Spanners
J-3847	J-3847	#14	Kikaya	Near electric pole, near Bahai temple	Manual	Drill, Saddle, Spanners
J-3854	J-3854	#15	Kikaya	20m off Kikaya-Kanyanya road, from Lover's Guesthse Poster, Adjacent Simex infant school, in fence, opposite 11/20/41, DN 50	Manual	Drill, Saddle, Spanners
J-3327	J-3327	#2	Naalya road	At valve 1645	None required	Spanners
J-3886	J-3886	#3	Kiwatule road	Near Decoration Centre	Manual	Drill, Saddle, Spanners
J-3313	J-3313	#3	Old Kira Road	At air valve 151	Manual	Spanners

Table A2-8a: Calibration Dataset Field Test Results – Pressure

DATASET 1 - CALIBRATION

PRESSURE TESTS

Time of recording - 10:00pm

Node	Pressure (kPa)
J-2923	370
J-2926	390
J-3080	550
J-3113	660
J-3190	630
J-3192	645
J-3247	260
J-3272	500
J-3289	780
J-3313	55
J-3327	890
J-3770	640
J-3775	320
J-3786	700
J-3828	710
J-3834	470
J-3841	500
J-3847	520
J-3854	805
J-3862	550
J-3879	430
J-3886	535

Time of recording - 15:00pm

Node	Pressure (kPa)
J-2923	380
J-2926	390
J-3080	540
J-3113	670
J-3190	650
J-3192	640
J-3247	270
J-3272	500
J-3289	770
J-3313	60
J-3327	910
J-3770	640
J-3775	330
J-3786	700
J-3828	700
J-3834	480
J-3841	510
J-3847	520
J-3854	820
J-3862	550
J-3879	420
J-3886	540

Table A2-8b: Calibration Dataset Field Test Results – Flow

FLOW TESTS

Time of recording - 10:00pm

Pipe	Discharge (l/s)
P-1956	10.65
P-1961	6.14
P-1969a	5.28
P-1987b	9.38
P-1989a	8.75
P-1999b	15.37
P-2000a	20.72
P-2003b	8.64
P-2004b	7.56
P-2639b	27.27
P-2644	4.13
P-2774b	9.33
P-2869d	12.06
P-2869f	9.84
P-2876a	8.21
P-3206	21.09
P-3207	4.53
P-3224	0.81
P-3237	1.37
P-3287	6.48

Time of recording - 15:00pm

Pipe	Discharge (l/s)
P-1956	8.74
P-1961	5.98
P-1969a	7.87
P-1987b	9.20
P-1989d	10.65
P-1999b	26.37
P-2000a	20.68
P-2003b	9.50
P-2004b	11.94
P-2639b	20.33
P-2644	11.44
P-2774b	11.37
P-2869d	0.26
P-2869f	16.82
P-2876a	3.75
P-3206	28.83
P-3207	0.44
P-3224	4.62
P-3237	1.69
P-3287	9.57

Table A2-9a: Post-Calibration Dataset 1 Field Test Results – Pressure

DATASET 2 - POST-CALIBRATION

PRESSURE TESTS

Time of recording - 10:00pm

Node	Pressure (kPa)
J-2849	500
J-2920	470
J-2925	350
J-2961	230
J-2990	360
J-2990	510
J-3061	250
J-3083	550
J-3085	750
J-3273	750
J-3292	550
J-3344	260
J-3581	250
J-3763	570
J-3765	220
J-3783	100
J-3793	450
J-3814	550
J-3823	260
J-3861	520
J-3874	500
J-3894	260

Time of recording - 15:00pm

Node	Pressure (kPa)
J-2849	500
J-2920	440
J-2925	370
J-2961	260
J-2990	360
J-2990	510
J-3061	250
J-3083	570
J-3085	750
J-3273	750
J-3292	550
J-3344	250
J-3581	250
J-3763	600
J-3765	210
J-3783	120
J-3793	450
J-3814	540
J-3823	280
J-3861	515
J-3874	480
J-3894	270

Table A2-9b: Post-Calibration Dataset 1 Field Test Results – Flow

FLOW TESTS

Time of recording - 10:00pm

Pipe	Discharge (l/s)
P-3304	22.41
P-3293	1.15
P-3201	27.43
P-2869e	11.54
P-2776g	4.42
P-2776e	7.39
P-2643b	10.01
P-2643a	12.44
P-2641b	13.08
P-2640c	15.21
P-2640a	15.56
P-2003c	10.12
P-2002b	14.31
P-2001	16.58
P-1999a	22.17
P-1989a	7.95
P-1954	9.18
P-1952	9.92
P-1948	10.40
P-1946b	13.09
P-1945a	13.18

Time of recording - 15:00pm

Pipe	Discharge (l/s)
P-3304	19.58
P-3293	0.98
P-3201	24.52
P-2869e	10.11
P-2776g	3.86
P-2776e	6.09
P-2643b	8.79
P-2643a	10.88
P-2641b	11.39
P-2640c	12.68
P-2640a	13.91
P-2003c	8.87
P-2002b	12.50
P-2001	13.66
P-1999a	19.46
P-1989a	7.35
P-1954	7.47
P-1952	9.66
P-1948	9.09
P-1946b	10.39
P-1945a	9.79

Table A2-10a: Post-Calibration Dataset 2 Field Test Results – Pressure

DATASET 3 - POST-CALIBRATION

PRESSURE TESTS

Time of recording - 10:00pm

Node	Pressure (kPa)
J-2921	610
J-2946	400
J-2966	300
J-3077	840
J-3079	460
J-3084	400
J-3282	810
J-3306	680
J-3764	410
J-3766	780
J-3792	710
J-3802	650
J-3817	580
J-3821	700
J-3827	400
J-3839	690
J-3851	520
J-3852	410
J-3872	820
J-3880	550
J-4046	730
J-2874	620

Time of recording - 15:00pm

Node	Pressure (kPa)
J-2921	400
J-2946	600
J-2966	270
J-3077	230
J-3079	320
J-3084	550
J-3282	390
J-3306	260
J-3764	500
J-3766	700
J-3792	520
J-3802	210
J-3817	550
J-3821	260
J-3827	50
J-3839	450
J-3851	120
J-3852	450
J-3872	540
J-3880	380
J-4046	260
J-2874	360

Table A2-10b: Post-Calibration Dataset 2 Field Test Results – Flow

FLOW TESTS

Time of recording - 10:00pm

Pipe	Discharge (l/s)
P-3305	23.33
P-3285	8.42
P-2868d	12.26
P-2776f	5.28
P-2776c	8.42
P-2776b	6.72
P-2775d	12.48
P-2003a	9.63
P-2002a	12.38
P-1998	31.71
P-1992b	9.69
P-1990	12.44
P-1972b	11.66
P-1969b	4.31
P-1963	9.77
P-1958	6.59
P-1953b	10.33
P-1335a	12.34
P-3302	32.99
P-2639c	16.12

Time of recording - 15:00pm

Pipe	Discharge (l/s)
P-3305	19.37
P-3285	7.09
P-2868d	12.74
P-2776f	3.52
P-2776c	6.83
P-2776b	6.44
P-2775d	8.60
P-2003a	8.86
P-2002a	13.53
P-1998	20.14
P-1992b	9.91
P-1990	10.80
P-1972b	7.93
P-1969b	4.41
P-1963	4.79
P-1958	7.41
P-1953b	7.15
P-1335a	12.85
P-3302	25.68
P-2639c	14.06

Table A2-11: Calibration Dataset (10am and 3pm) Calibration Results Excerpt

Fitness: 3909.333740			
	Multiplier	Multiplier	
Roughness Adjustments	[adjusted]	[original]	
Roughness Group - HDPE (1995 - 1999)	0.90	1.00	
Roughness Group - GI (1995 - 1999)	0.80	1.00	
Roughness Group - PVC (1995 - 1999)	1.00	1.00	
Roughness Group - STEEL (1950 - 1954)	0.98	1.00	
Roughness Group - STEEL (1955 - 1959)	0.92	1.00	
Roughness Group - STEEL (1960 - 1964)	0.93	1.00	
Roughness Group - STEEL (1965 - 1969)	1.00	1.00	
Roughness Group - STEEL (1970 - 1974)	0.90	1.00	
Roughness Group - STEEL (1975 - 1979)	1.00	1.00	
Roughness Group - STEEL (1995 - 1999)	1.00	1.00	
Demand Adjustments (l/s)	[adjusted]	[original]	
Demand Group - (0.00 - 0.09)	1.53	1.00	
Demand Group - (0.10 - 0.19)	1.49	1.00	
Demand Group - (0.20 - 0.29)	1.00	1.00	
Demand Group - (0.30 - 0.39)	1.72	1.00	
Demand Group - (0.40 - 0.49)	1.00	1.00	
Demand Group - (0.50 - 0.59)	1.70	1.00	
Demand Group - (0.60 - 0.69)	1.00	1.00	
Demand Group - (0.70 - 0.79)	1.50	1.00	
Demand Group - (0.80 - 0.89)	1.00	1.00	
Demand Group - (0.90 - 0.99)	1.07	1.00	
Demand Group - (1.00 - 1.09)	1.00	1.00	
Demand Group - (1.10 - 1.19)	1.43	1.00	
Demand Group - (1.20 - 1.29)	1.55	1.00	
Demand Group - (1.30 - 1.39)	1.08	1.00	
Demand Group - (1.40 - 1.49)	1.62	1.00	
Demand Group - (1.50 - 1.59)	1.24	1.00	
Demand Group - (1.60 - 1.69)	1.01	1.00	
Demand Group - (1.70 - 1.79)	1.34	1.00	
Demand Group - (1.90 - 1.99)	1.52	1.00	
Demand Group - (2.00 - 6.00)	1.40	1.00	
HGL Observations (m)	[simulated]	[observed]	[difference]
Calibration 10am			<RMSE: 26.12>
J-2923	1,247.18	1,231.47	15.71
J-2926	1,254.91	1,238.51	16.39
J-3080	1,241.15	1,229.98	11.16
J-3113	1,246.82	1,223.96	22.86
J-3190	1,256.44	1,225.69	30.75
J-3192	1,257.22	1,244.11	13.10
J-3247	1,258.73	1,283.07	-24.34
J-3272	1,257.07	1,231.56	25.51
J-3289	1,258.73	1,202.51	56.22
J-3313	1,218.17	1,239.64	-21.47
J-3327	1,267.31	1,233.18	34.14
J-3770	1,264.57	1,254.18	10.40
J-3775	1,241.50	1,213.11	28.39

Table A2-12: Post-Calibration Dataset 1 (10am and 3pm) Calibration Results Excerpt

Fitness: 5163.673340			
Roughness Adjustments	[adjusted]	[original]	
Roughness Group - HDPE (1995 - 1999)	0.90		
Roughness Group - GI (1995 - 1999)	0.80		
Roughness Group - PVC (1995 - 1999)	1.00		
Roughness Group - STEEL (1950 - 1954)	0.98		
Roughness Group - STEEL (1955 - 1959)	0.92		
Roughness Group - STEEL (1960 - 1964)	0.93		
Roughness Group - STEEL (1965 - 1969)	1.00		
Roughness Group - STEEL (1970 - 1974)	0.90		
Roughness Group - STEEL (1975 - 1979)	1.00		
Roughness Group - STEEL (1995 - 1999)	1.00		
Demand Adjustments (l/s)	[adjusted]	[original]	
Demand Group - (0.00 - 0.09)	1.53		
Demand Group - (0.10 - 0.19)	1.49		
Demand Group - (0.20 - 0.29)	1.00		
Demand Group - (0.30 - 0.39)	1.60		
Demand Group - (0.40 - 0.49)	1.00		
Demand Group - (0.50 - 0.59)	1.70		
Demand Group - (0.60 - 0.69)	1.00		
Demand Group - (0.70 - 0.79)	1.50		
Demand Group - (0.80 - 0.89)	1.00		
Demand Group - (0.90 - 0.99)	1.07		
Demand Group - (1.00 - 1.09)	1.00		
Demand Group - (1.10 - 1.19)	1.43		
Demand Group - (1.20 - 1.29)	1.55		
Demand Group - (1.30 - 1.39)	1.08		
Demand Group - (1.40 - 1.49)	1.62		
Demand Group - (1.50 - 1.59)	1.24		
Demand Group - (1.60 - 1.69)	1.01		
Demand Group - (1.70 - 1.79)	1.34		
Demand Group - (1.90 - 1.99)	1.52		
Demand Group - (2.00 - 6.00)	1.40		
HGL Observations (m)	[simulated]	[observed]	[difference]
PostCal 1 10am			<RMSE: 30.58>
J-2849	1,283.41	1,262.07	21.34
J-2920	1,248.21	1,259.01	-10.79
J-2925	1,257.78	1,249.75	8.03
J-2961	1,250.54	1,230.49	20.05
J-2991	1,243.66	1,251.77	-8.11
J-2990	1,242.99	1,258.09	-15.10
J-3061	1,240.18	1,224.54	15.64
J-3083	1,242.78	1,259.18	-16.39
J-3085	1,241.95	1,279.61	-37.66
J-3273	1,260.71	1,286.61	-25.90
J-3292	1,259.37	1,261.18	-1.80
J-3344	1,251.35	1,218.56	32.79
J-3581	1,260.33	1,209.54	50.80
J-3763	1,275.97	1,272.22	3.75

Table A2-13: Post-Calibration Dataset 2 (10am and 3pm) Calibration Results Excerpt

Fitness: 5927.296387			
Roughness Adjustments	[adjusted]	[original]	
Roughness Group - HDPE (1995 - 1999)	0.90		
Roughness Group - GI (1995 - 1999)	0.80		
Roughness Group - PVC (1995 - 1999)	1.00		
Roughness Group - STEEL (1950 - 1954)	0.98		
Roughness Group - STEEL (1955 - 1959)	0.92		
Roughness Group - STEEL (1960 - 1964)	0.93		
Roughness Group - STEEL (1965 - 1969)	1.00		
Roughness Group - STEEL (1970 - 1974)	0.90		
Roughness Group - STEEL (1975 - 1979)	1.00		
Roughness Group - STEEL (1995 - 1999)	1.00		
Demand Adjustments (l/s)	[adjusted]	[original]	
Demand Group - (0.00 - 0.09)	1.53		
Demand Group - (0.10 - 0.19)	1.49		
Demand Group - (0.20 - 0.29)	1.00		
Demand Group - (0.30 - 0.39)	1.60		
Demand Group - (0.40 - 0.49)	1.00		
Demand Group - (0.50 - 0.59)	1.70		
Demand Group - (0.60 - 0.69)	1.00		
Demand Group - (0.70 - 0.79)	1.50		
Demand Group - (0.80 - 0.89)	1.00		
Demand Group - (0.90 - 0.99)	1.07		
Demand Group - (1.00 - 1.09)	1.00		
Demand Group - (1.10 - 1.19)	1.43		
Demand Group - (1.20 - 1.29)	1.55		
Demand Group - (1.30 - 1.39)	1.08		
Demand Group - (1.40 - 1.49)	1.62		
Demand Group - (1.50 - 1.59)	1.24		
Demand Group - (1.60 - 1.69)	1.01		
Demand Group - (1.70 - 1.79)	1.34		
Demand Group - (1.90 - 1.99)	1.52		
Demand Group - (2.00 - 6.00)	1.40		
HGL Observations (m)	[simulated]	[observed]	[difference]
PostCal 2 10am			<RMSE: 32.14>
J-2921	1,248.21	1,246.05	2.16
J-2946	1,238.99	1,239.90	-0.91
J-2966	1,250.55	1,251.81	-1.27
J-3077	1,242.16	1,201.54	40.62
J-3079	1,242.26	1,230.75	11.51
J-3084	1,244.38	1,255.11	-10.73
J-3282	1,270.33	1,226.79	43.54
J-3306	1,268.86	1,217.56	51.30
J-3764	1,275.99	1,278.33	-2.34
J-3766	1,267.73	1,265.61	2.13
J-3792	1,260.52	1,260.50	0.02
J-3802	1,255.35	1,244.18	11.17
J-3817	1,267.31	1,217.54	49.77